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A MODEL FOR THE TRANSIENT METABOLIC THERMAL RESPONSE OF MAN IN SPACE

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ABSTRACT

A mathematical model of the thermal responses of man in space is presented. The model describes the heat-transfer processes within the human body, simulates the human thermoregulatory system, and determines the thermal interchange of man with his environment. Any environment can be utilized with the model, whether it be deep space or earth sea level conditions. Space suit and spacecraft cabin environments are also considered.

The model has the additional capability of determining the thermophysical effects of any environment upon a man's comfort and well being.

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INTRODUCTION

This report describes a model for the thermal regulatory system of the human body; particularly its application for use in the severe environments encountered in Project Apollo. The report initially presents a generalized, simplified view of the model. The basic equations of heat transfer are then derived and subsequently, a detailed explanation of each of the terms of these equations is presented. This includes heat generation terms (QMET, QSHIV), heat removal terms (QCOND, QCONV, QRAD, QLCG, QSEN, QLAT, QUG), heat storage terms (QSTOR, STORAT), thermoregulatory control terms (SWEAT, QSHIV, DILAT, STRICT), and various skin temperatures.

The remainder of the report is a discussion of the environmental modes of operation considered. These include normal shirtsleeve operation, operation in a spacesuit (intravehicular and extravehicular), and operation in a post-landing environment. The spacesuit and shirtsleeve analyses may be considered in a closed environment such as a spacecraft cabin, or an open environment such as a flat plain. The post-landing analysis is grouped under MISCELLANEOUS CALCULATIONS and treats the problem of carbon dioxide, water vapor, and temperature buildup associated with a closed cabin having limited gas flow. The report appendix contains the specific equations considered for each compartment of the human body.

1.0. MODEL OF THE THERMAL REGULATORY SYSTEM OF THE HUMAN BODY

The human body may be considered in the same light as a heat engine. That is, heat is produced (QMET) by the oxidation of fuel (food) for energy, and heat is dissipated by conduction, convection, radiation and mass transfer at the skin surfaces. Heat produced in excess of that which can be dissipated will be stored in the tissues (QSTOR), with a resulting rise in body temperatures. Values of QSTOR in excess of 400 Btu's are equivalent to high body temperatures indicative of life function deterioration. The heat balance is depicted in Figure 1.

The simulation model divides the body into six elements; head, trunk, arms, hands, legs, and feet. Each consists of central blood, core and/or muscle, and skin nodes. There are fourteen distinct compartments, each compartment assumed to be at a uniform temperature and having a discreet temperature distribution (Figure 2).

Heat generated in each compartment (QMET), is transmitted by convection to the blood (QCONV), and by conduction to adjacent compartments(QCOND). For skin compartments, convection to a gas stream (QSEN), radiation to walls or the suit interior surfaces (QRAD), latent evaporation (QLAT), and conduction to a thermal undergarment (QUG), with selective conduction to a liquid cooled garment (QLCG)*, are all considered as avenues of heat dissipation.

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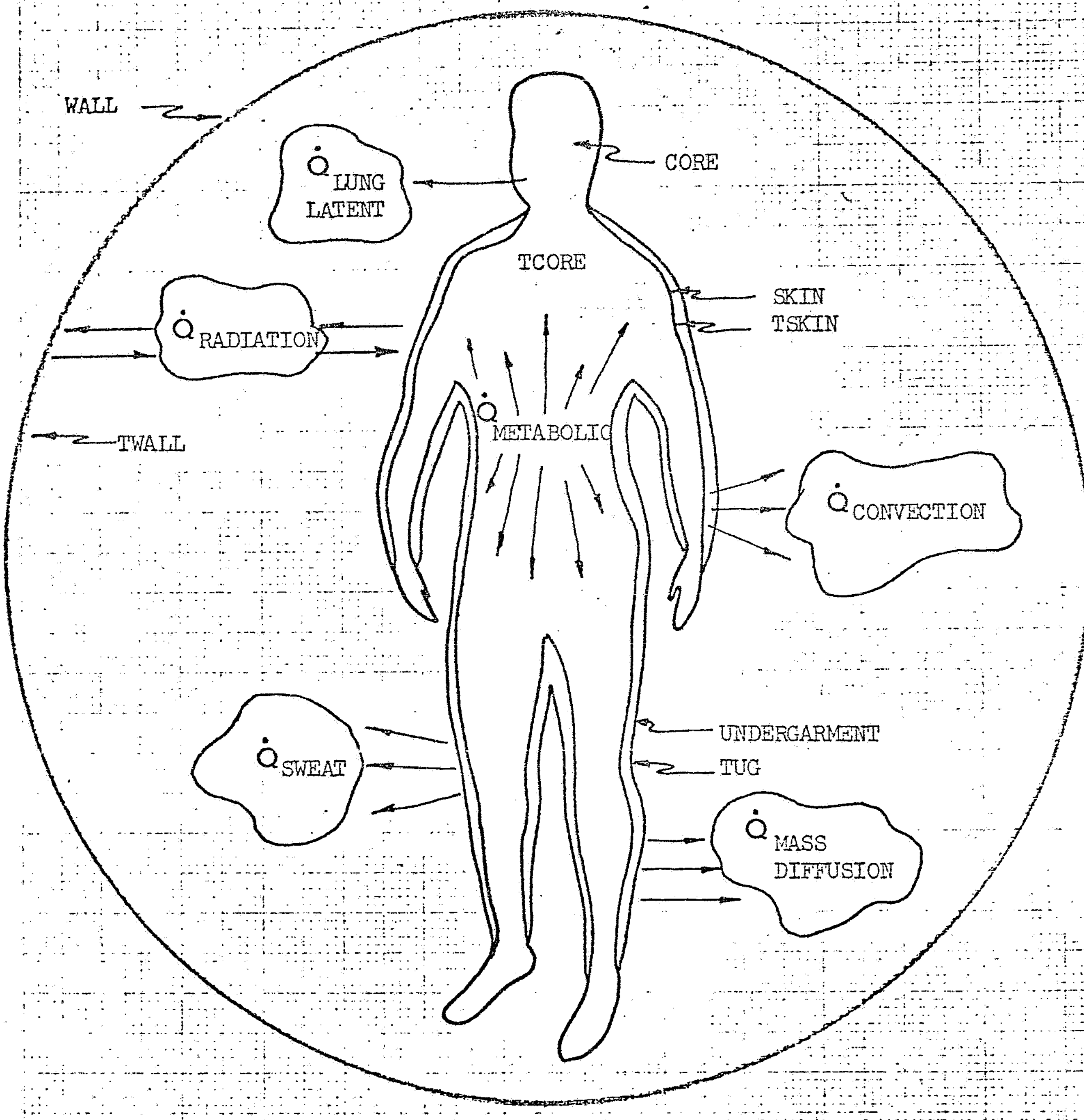
*Optional



THERMAL BALANCE FOR MAN IN SPACE

$$\overbrace{\dot{Q}_{\mathrm{METABOLIC}}}^{\text{HEAT PRODUCED}} - \overbrace{\dot{Q}_{\mathrm{CONVECTION}} - \dot{Q}_{\mathrm{MASS\ DIFFUSION}} - \dot{Q}_{\mathrm{SWEAT}} - \dot{Q}_{\mathrm{LUNG\ LATENT}} - \dot{Q}_{\mathrm{RADIATION}}}^{\text{HEAT DISSIPATED}} = \underbrace{\dot{Q}_{\mathrm{STORED}}}_{\text{HEAT STORED}}$$

FIGURE 1

DISCREET MODEL

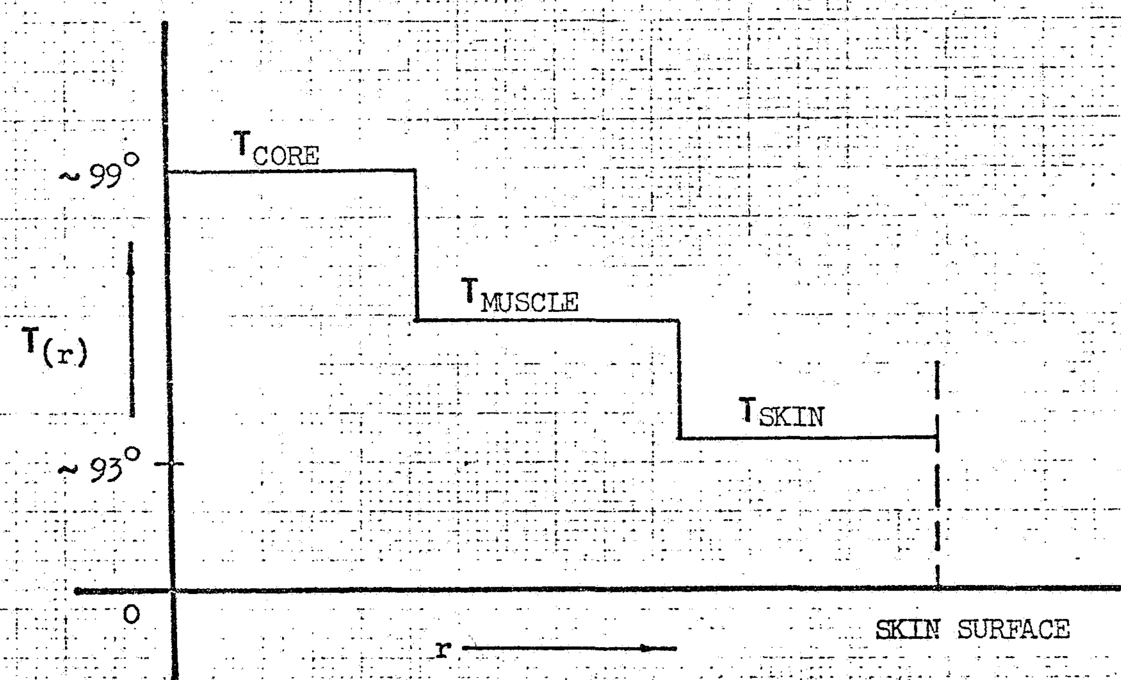


FIGURE 2

The general equation for each compartment is written in the form of a heat balance: Simply: Heat Stored = Heat in - Heat out

For the core: (See Figure 3)

$$[\text{Mass}]\,[C_p]_{\text{core}} \frac{d\,T\text{core}}{dt} = \text{QMET}_{\text{core}} - \text{QCOND} - \text{QCONV}''$$

For the muscle:

$$[\text{Mass}]\,[C_p]_{\text{muscle}} \frac{d\,T\text{muscle}}{dt} = \text{QMET}_{\text{muscle}} + \text{QCOND} - \text{QCOND}' - \text{QCONV}'$$

For the skin:

$$[\text{Mass}]\,[C_p]_{\text{skin}} \frac{d\,T\text{skin}}{dt} = \text{QMET}_{\text{skin}} + \text{QCOND}' - \text{QCONV} - \text{QRAD} - \text{QSEN} - \text{QLAT} - \text{QLCG}\ ^{*}$$

The muscle compartment is added for regions of the body having considerable muscular development. This includes all compartments except the head. For the trunk, the muscle compartment is sandwiched between the core and the skin. For the extremities (which are mostly muscle) the muscle compartment replaces the core. The heat balance procedure for each compartment follows the general guidelines outlined above and is shown in Appendix A.

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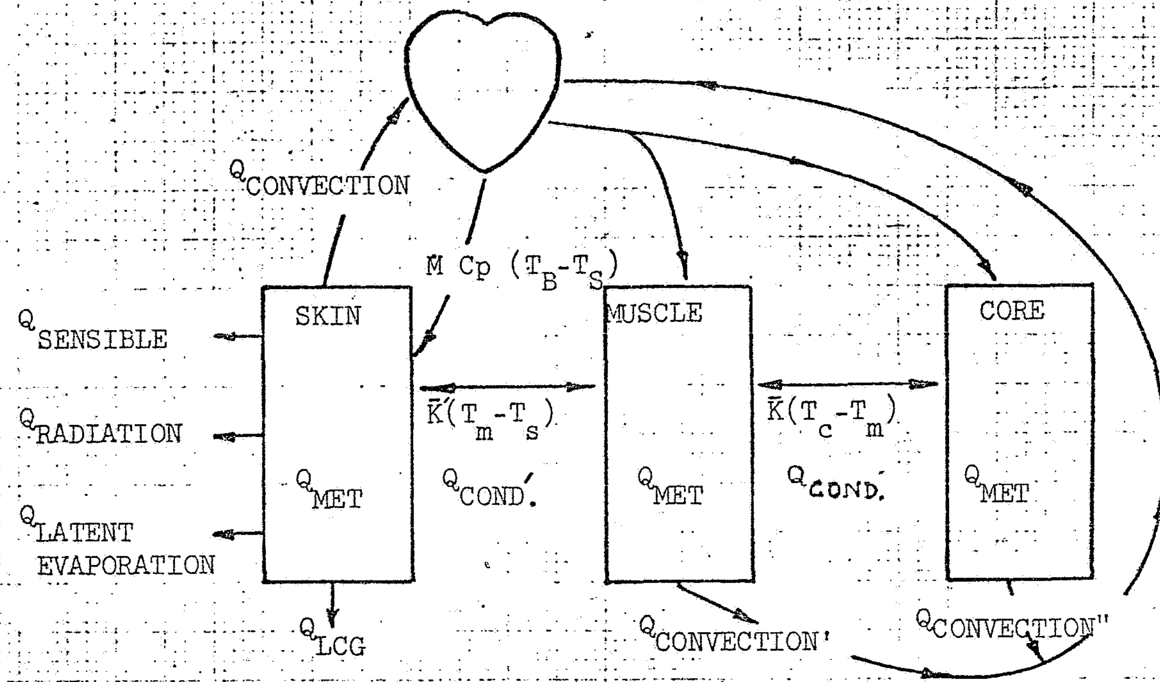
*Option

DISCREET TEMPERATURE DISTRIBUTION



TYPICAL HEAT BALANCE FOR SKIN SEGMENT

$$\bar{K}'(T_{MUSCLE}-T_{SKIN}) + \dot{M}C_p(T_{BLOOD}-T_{SKIN}) + Q_{METABOLIC\ GENERATED}$$

$$-Q_{RADIATION} - Q_{SENSIBLE} - Q_{LATENT\ EVAPORATION}$$

$$= (MASS_{SKIN})(Cp_{SKIN})\ \frac{dT_{SKIN}}{dt}$$

FIGURE 3

QMET

The heat generated by the body (QMET or RM) consists of a basal metabolic rate for each compartment and a work rate over and above this, required for performing every-day tasks. This excess work is generated in the muscle compartments, and, as a consequence of the relative inefficiency of the body as a heat engine, most of the work is lost in the form of heat. That work which is not lost is converted directly into mechanical energy (U), required to perform a given task. Heat may also be generated by shivering. Thus, RM may be increased above basal (284 Btu/hr) by either imposing a work load on the muscles or shivering. Shiver (QSHIV) is actually a measure of the amount of heat that must be generated metabolically to prevent the body from losing more heat than it is producing. This situation can only occur in cold environments. The mathematical representation of QSHIV will be described subsequently in ACTIVE CONTROLLERS.

We may now write the expression for exercise rate or work as follows:

$$\text{WORK} = \text{RM} - 284. - \text{U} \qquad \text{Btu/hr}$$

This is the work actually produced in the muscle tissues that will enter into the heat balance (since it is all converted to heat). The heat generated by WORK is divided on a percentage basis among the trunk, arm, and leg muscle. The extremity muscles are not considered as a significant source of WORK.

MECHANICAL WORK EFFICIENCY, UEFF

Mechanical work efficiency (UEFF) is defined such that the net mechanical work performed by a crewman on his surroundings is:

$$U = \frac{UEFF}{100.} \quad (RM - 284.)$$

The total basal metabolic rate required for basic maintenance of the body is approximately 284 Btu/hr. UEFF, mechanical work efficiency, is actually a function of metabolic rate and the type of work being done.

QCOND

Radial conduction between compartments is characterized by heat transfer between two or three discrete layers of body tissue, each assumed to be at a uniform temperature. Heat transfer is one dimensional and is likened to conduction through a wall. It is assumed that lateral conduction is negligible.

Therefore, we may write

$$\text{QCOND} = \frac{KA}{L} \Delta T \qquad \text{Btu/hr}$$

Values of $\frac{KA}{L}$ are determined empirically for each of the separate compartments. Thus, we may finally write the conduction terms for the trunk compartment as follows:

$$\text{QCOND} = \bar{K}(T_{core} - T_{muscle})_{trunk} \qquad \text{for trunk core to trunk muscle}$$

$$\text{QCOND}' = \bar{K}'(T_{muscle} - T_{skin})_{trunk} \qquad \text{for trunk muscle to trunk skin}$$

QCONV

Heat is transmitted to and from every living cell in the body by the bloodstream. With increased metabolism due to work, shivering or emotional reactions, blood flow is varied from the basal rate to provide those tissues producing additional energy with an adequate fuel supply. This also serves to carry away the increased production of waste products that is a consequence of elevated metabolic rates. Since increases in QMET occur almost exclusively in the trunk, arm, and leg muscle compartments, it is not surprising that increases in blood flow (and thus QCONV) resulting from metabolism increases, are also limited to these compartments. QCONV, the total heat transferred to the tissues from the bloodstream is given as:

$$\mathrm{QCONV} = \dot{m}c_p(T_{blood} - T) \qquad \mathrm{Btu/hr}$$

where QCONV is the heat transferred from each compartment, $\dot{m}$ is the blood flow rate through each compartment, c_p is the specific heat of the blood, T_{blood} is the temperature of the central blood pool and T is the temperature of the individual compartment. Thus, for example, we may write for the trunk core:

$$\mathrm{QCONV}_{\substack{trunk\\core}} = (\dot{m}\,c_p)_{\substack{trunk\\core}}(T_{blood} - T_{\substack{trunk\\core}}) \qquad \mathrm{Btu/hr}$$

It should be mentioned that the arterial bloodstream temperature is assumed to be uniform throughout the body. That is, a central blood pool contacts all tissue compartments. The speed with which oxygenated blood leaves the heart and is distributed to the tissues is such that it can be reasonably assumed to be isothermal. As previously mentioned, increases in metabolic rate propagate corresponding increases in $\dot{m}$ for the arm, leg, and trunk muscle compartments. The blood flow rate to the extremity skin compartments can also be regulated. This is effected as a result of vasodilation or vasoconstriction, two of the mechanisms utilized by the thermoregulatory system for maintaining constant deep body temperatures. These mechanisms are subsequently described in ACTIVE CONTROLLERS.

Thus, it can be seen that blood flow to the muscles and skin compartments may be varied in response to metabolic rate and environmental conditions. It is interesting to note that $\dot{m}$ to core compartments remains unchanged, regardless of external conditions. This is in accordance with the fact that energy requirements of the brain, and other vital organs remain within narrow bounds. Consequently, blood flow rates to these regions does not vary significantly.

QSEN

Heat removal at the skin surface occurs by convection, evaporation of moisture, conduction to an undergarment and radiation. Convective heat transfer to a surrounding gas stream (QSEN) is limited due to the low specific heat of oxygen or air. This is especially so in a space suit where gas flow rate becomes an additional limitation. The amount of heat removed by sensible convection to a gas stream is:

$$QSEN = h\ A\ (T_{skin} - \overline{T}_{gas})\ \ \text{Btu/hr}\ ,$$

where A is skin compartment surface area, h is the heat transfer coefficient, and $\overline{T}_{gas}$ is a mean gas stream temperature. The evaluation of $\bar{h}$ and $\overline{T}_{gas}$ for shirtsleeve and space suit operation will be described subsequently in 2.0.

QRAD

Radiation heat transfer from the skin compartments can become significant in spacecraft environments. For each skin compartment, we determine:

$$QRAD = AR\,\sigma\,\mathcal{F}(T_{skin}^{4} - T_{wall}^{4}) \;, \quad Btu/hr$$

where $\sigma = 1713 \times 10^{-12}$

AR = radiation area of skin compartment, ft.^{2}

$\mathcal{F}$ = Script F interchange factor

T_{wall} = spacecraft or cabin wall temperature (or suit interior wall temperature for suited operation)

T_{skin} and T_{wall} are in ^{o}R

The script F interchange factor depends upon system geometry and surface coatings. It will be evaluated subsequently in 2.0.

QLAT

The most significant and controllable element that the human thermoregulatory system has at its disposal is the production of sweat. Normally, under comfort conditions, a rather nominal quantity of water evaporates from the skin surface by simple gaseous diffusion (QDIF). This will be explained further in MISCELLANEOUS HEAT TRANSFER PATHS. Suffice it to say that water is a normal by-product of the body's metabolic processes, and since the partial pressure of water at the surface of the skin is usually greater (due to these processes) than the partial pressure of water in the surrounding atmosphere, diffusion will occur. However, if metabolism (and consequently heat generation) is increased due to heavy work loads, etc., diffusion, radiation and sensible convection may not be enough to dissipate the excessive production of heat. If this occurs, body temperatures begin to rise. If these temperatures increase appreciably above their set point or normal values, certain geometrically distributed sweat glands pour excess water (resulting from the increased metabolic rate) onto the skin surface (SWEAT). The sweat on the surface of the skin will then absorb heat as it evaporates. The model calculates SWEAT for each skin compartment. It is a control function and depends upon the temperature differential of certain critical body temperatures from their norm values. It will be evaluated in greater detail in ACTIVE CONTROLLERS. As long as the environment (suited or shirtsleeve) remains within certain bounds, all of the SWEAT on the skin compartment surface will be evaporated. However, if the environment is such that the maximum amount of sweat that can be evaporated (EMAX) is less than the amount being produced (SWEAT), then the body will not be able to dissipate the difference, and consequently, will store heat.

This maximum evaporative capacity, EMAX, is simply the mass transfer expression:

$$\text{EMAX} = h_D A(\text{VPP}(T_{skin}) - \text{VPP}(T_{dewc})) * 1040, \quad \text{Btu/hr}$$

where h_D is a mass transfer coefficient,

A is the skin compartment area, and

VPP (T_{skin}) and VPP (T_{dewc}) are partial water vapor pressures evaluated at the skin surface and in the gas stream, respectively. The evaluation of h_D will be discussed further in 2.0.

QLCG

To remove excess heat generated during high work loads, a liquid cooled garment (LCG) has been developed for Apollo astronauts. The garment utilizes cool water through a network of small tubes covering the skin to absorb heat and avoid or reduce heat storage. During extravehicular activities (EVA), this mode of heat removal is the most significant. The model simulates the LCG heat removal (QLCG) by equating water temperature rise across the LCG with heat transfer from the skin to the water. Thus,

$$QLCG = WF\ C_p\ (TW_{out} - TW_{in}) = UA(T_{skin} - \bar{T}_{water})\ \ \text{Btu/hr}$$

where WF = LCG water flow rate, lbs./hr

C_p = Specific heat of liquid (= 1 for water), Btu/lb-°F

TW_{in} = water inlet temp. (input), °F

TW_{out} = water outlet temperature, °F

UA = LCG effectiveness (determined empirically), Btu/hr-°F

T_{skin} = Skin compartment temperature, °F

$\bar{T}_{water}$ = logarithmic mean water temperature derived to be:

$$\bar{T}_{water} = T_{skin} - (1 - e^{-[UA/[(WF)(C_p)]]})\ (T_{skin} - TW_{in})(WF)(C_p)/UA$$

The current LCG covers only the trunk, arms, and legs and is split up in the model on a percentage water flow basis. It may be called as an option in the program during shirtsleeve or suited operation.

In addition, there is a small subroutine available which simulates the sublimator - liquid cooled garment interaction of the Apollo PLSS (portable life support system). This optional routine calculates the LCG inlet water temperature based upon the manually selected position of the sublimator diverter valve. For maximum, intermediate, and minimum cooling, 240, 30, and 9 lbs of coolant per hour, respectively, are passed through the PLSS sublimator.

A temperature controller routine is available in this subroutine to simulate the subjective response of the crewman to the LCG. Specifically, if the crew shiver rate (QSHIV) exceeds 50 Btu's/hr, the diverter valve is operated to reduce flow to the sublimator and increase inlet water temperature. Conversely, if QSTOR exceeds 50 Btu's, flow to the sublimator is increased to lower LCG inlet temperature.

MISCELLANEOUS HEAT TRANSFER PATHS

In addition to those modes of heat removal previously discussed, there are several additional methods that the body utilizes. For the most part, these miscellaneous avenues do not account for much heat removal; however, at high metabolic rates, they may contribute significantly towards maintaining stable body temperatures. These paths are described below:

a. Respiratory sensible loss - convective heat transfer through the lungs and respiratory tract. Determined empirically as

$$QRSEN = \frac{0.0418(Pgas)(144)(Rm)\ ((Tcore_{head} + Tcore_{trunk}) - \overline{Tgas})\ Cp}{48.3\ (\overline{Tgas} + 460)}$$

where $\overline{Tgas}$ is the mean gas stream temperature near the head.

b. Respiratory latent loss - evaporative mass transfer through the lungs and respiratory tract. Determined empirically as

$$QR = 0.0418(Pgas)(144)(Rm)\ (VPP\ ((Tcore_{head} + Tcore_{trunk})) - 0.8VPP(Tdewc))\ \frac{(18)(1040)}{(32)(Pgas)}$$

c. Skin diffusion - evaporative loss of moisture from the skin by diffusion. Determined empirically as $QDIF = 6.66A\ (VPP(T_{skin}) - VPP(Tdewc))$ Btu/hr

where T_{skin} is the skin compartment temperature (or undergarment temperature for those compartments covered with clothing).

STORAT

The instantaneous thermal disposition of the human body is evaluated by performing a heat balance on the overall system.

That is:

$$STORAT = RM + QSHIV - (\overbrace{QEVAP + QDIF + QR}^{QLAT} + QRSEN + QRAD + QLCG + QSEN + U) \quad Btu/hr$$

If STORAT is positive, the net, cumulative, instantaneous heat transfer is from the environment to the body. If STORAT is negative the net heat transfer is from the body to the environment. STORAT is not to be used as a physiological guide for crew condition, but only as a means of monitoring the instantaneous direction of heat transfer. When STORAT approaches and converges near zero, the crewman is assumed to have reached steady state conditions.

QSTOR

Heat produced in excess of that which can be dissipated will be stored in the tissues with a resulting rise in body temperature. Heat storage (QSTOR) is calculated according to:

$$QSTOR = \sum_{\substack{I = \text{all} \\ \text{body} \\ \text{compartments}}} C(I) \left(T(I) - T_{SET}(I)\right) \quad , \text{Btu's}$$

Where $C(I)$ is the heat capacitance of each body compartment, $T(I)$ is the compartment temperature, and $T_{SET(I)}$ is the set point or normal compartment temperature. Values of QSTOR in excess of 300 Btu's indicate an interruption of normal performance. That is, normal crew performance is likely impaired. Values of QSTOR in excess of 400 Btu's are equivalent to high body temperature or moderate fever, with a distinct possibility of collapse. If QSTOR exceeds 750 Btu's, life function deterioration is advanced, frequently with fatal results.

QUG.

The model accounts for heat which passes through a thermal undergarment (QUG). That is, in both the shirtsleeve and suited subroutines, the undergarment temperature is determined by balancing heat transferred from the skin to the undergarment by conduction with heat transferred away from the undergarment by radiation and convection. Specifically:

$$K_{UG}(T(I) - TUG(I)) = QSEN + QRAD$$

where K_{UG} = undergarment conductance.

For those skin compartments covered by the undergarment, heat and mass transfer occurs from the undergarment to the gas stream or wall. For those skin compartments not covered by the undergarment (head, hands, and feet), heat and mass transfer occurs from the skin directly to the gas stream or wall.

ACTIVE CONTROLLERS*

The body has four primary controllers for maintaining itself in an essentially isothermal state. These are:

a. Sweat production.

b. Shivering.

c. Vasodilation

d. Vasoconstriction

*NOTE: The equations describing active human thermoregulatory control are highly empirical. The state of the art is such that these equations are especially subject to change.

SWEAT

Active sweating is initiated when all other mechanisms of heat removal are insufficient for dissipating metabolic heat production. As body temperatures rise and heat storage (QSTOR) increases, temperature sensors in the skin and the hypothalamic region of the brain detect deviations and activate the sweat glands. It is not surprising then, that the equation describing the control of sweat is a function of the positive deviation of the head core, muscle, and skin compartment temperatures from their normal or set point values. In fact, J. B. Pierce Laboratories has empirically described sweat production as:

$$\text{SWEAT} = 73.4814\,(T_{core} - T_{core\ set})_{head}\left(\sum_I K(I)\,(T(I) - TSET(I)) + \sum_J K(J)(T(J) - TSET(J))\right),\ \text{Btu's/hr}$$

I = all skin compartments
J = all muscle compartments

where the K(I)'s and K(J)'s are constants based on the weighted mass of each compartment. The equation is only valid for positive deviations greater than zero. Furthermore, if the head core (hypothalamic) signal is zero, sweating is terminated throughout.

QSHIV

Active shivering is analagous but exactly opposite to sweating. The body shivers to effectively increase metabolic rate in order to compensate for excess heat loss. The QSHIV signal is identical to the SWEAT signal, except in the opposite direction. Again, all deviations less than zero are cancelled out. Hence:

$$QSHIV = 73.4814\,(T_{core\ set} - T_{core})_{head}\ \Big(\sum_{I = \text{all skin compartments}} K(I)(TSET(I) - T(I)) + \sum_{J = \text{all muscle compartments}} K(J)\,(TSET(J) - T(J))\Big),\ \text{Btu's/hr}$$

DILAT

Vasodilation is the controlled enlargement or dilation of blood vessels to the extremeties (skin compartments). In a hot environment, the body attempts to deliver more blood from the critical deep tissues to the less important extremeties. By increasing blood flow to the skin compartments, more heat is carried away from the muscle and core compartments. This has the effect of maintaining stable deep body temperatures while elevating skin temperatures. The high skin temperatures, in turn, activate or increase the SWEAT mechanism. It is reasonable then, that the vasodilation control, activated when the body is storing heat, is influenced by the same factors as the SWEAT mechanism. In fact, vasodilation has been empirically determined to be:

$$\text{DILAT} = \text{SWEAT}/4 \qquad \text{lbs/hr}$$

STRICT

Vasoconstriction is the controlled constriction of blood vessels to the muscle and skin compartments in order to conserve heat in the critical head and trunk core regions. In a cold environment, the body attempts to maintain normal core temperature in the head and trunk at the expense of all other regions. The vasoconstriction mechanism does not require a head core signal as does vasodilation. The assumption is that the body would like to prevent shivering at all costs. Thus, blood flow to all muscle and skin compartments is restricted in an attempt to maintain an isothermal head core temperature and avoid shivering. Vasoconstriction is empirically determined to be:

$$\mathrm{STRICT} = .01961 \Big(\sum_{I = \text{all skin compartments}} K(I)(TSET(I) - T(I)$$

$$+ \sum_{J = \text{all muscle compartments}} K(J)((TSET(J) - T(J))) \quad \text{lbs/hr}$$

2.0 MODES OF OPERATION

2.1 SHIRTSLEEVE MODE

Subroutine SHIRT considers a man in a spacecraft, or for that matter, any environment, wearing an undergarment with variable properties. The heat transfer paths are shown schematically in Figure 4. The cabin or environmental conditions may be constant or read in from a table. For the shirtsleeve mode, the human thermal environment is strictly input. The man model is broken up into the usual number of compartments, with each compartment seeing the same environment.

HEAT TRANSFER PATHS

(SHIRTSLEEVE MODE)

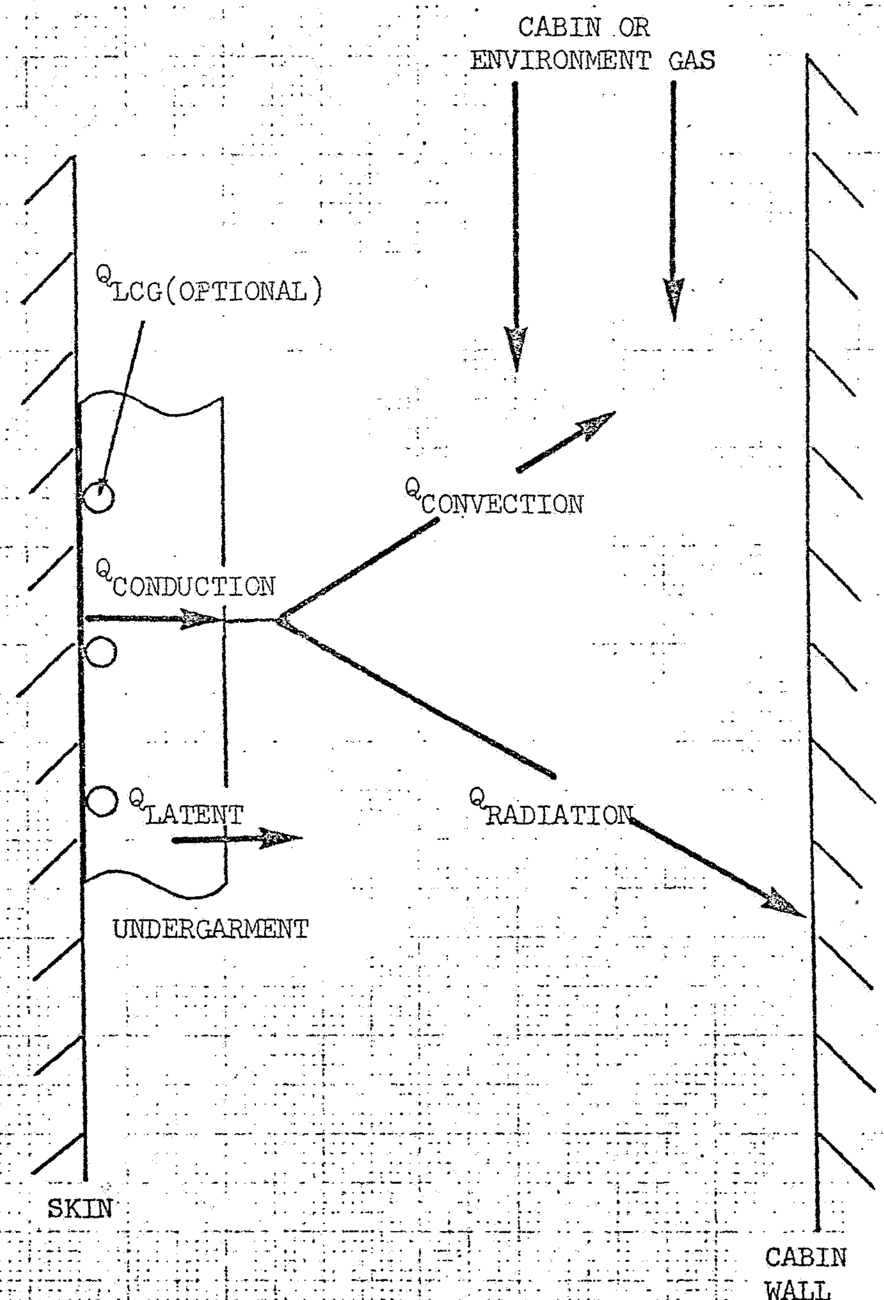


FIGURE 4

QSEN

The convective heat transfer for each skin compartment in the shirtsleeve environment is calculated from:

QSEN = .0212*ACE(I) * (PCAB * VCAB)** .5*(TUG(I) - TCAB)[+]

for forced convection, and

QSEN = .06 * ACE(I) * (PCAB ** 2 * G * ABS(TUG(I) - TCAB)) ** .25 * (TUG(I) - TCAB)

for free convection.

Both of these expressions are derived from an analysis of flow perpendicular to a vertical cylinder, utilizing the dimensions of the average astronaut. Expressions resulting from evaluation of flow parallel to a flat plate are not appreciably different. For environments in a gravity field (G>0), the larger of forced or free convection coefficients is used to calculate QSEN.

[+]NOTE: Equations using the symbols * for multiplication, ** for exponentiation and / for division are written in Fortran.

EMAX

The maximum evaporative capacity in the shirtsleeve mode, EMAX, is calculated for each skin compartment from:

```
EMAX = .126 * ACE(I) * ((TCAB + 460.) ** 1.04) *
        VEFF/100 * SQRT (VCAB/PCAB) * (VPP(TUG(I) - VPP (TDEW)), Btu's/hr
```

for forced convection.

and

```
EMAX = 1.32 * ACE(I) * (TCAB + 460.) * (VPP(TUG(I) -
        VPP(TDEW)) *(PCAB * G *(ABS(.005*PCAB* (TUG(I) - TCAB) +
        1.02 * (VPP(TUG(I)  - VPP(TDEW))))** .25/PCAB, Btu's/hr
```

for free convection.

Both of these expressions are derived by applying the heat-mass transfer analogy to the vertical cylinder model discussed previously. Again, for environments in a gravity field, (G>0) the larger of the two mass transfer coefficients is utilized to calculate EMAX.

QRAD

Radiation heat transfer for each skin compartment is calculated in subroutine SHIRT by:

$$QRAD = .1713E - 8 * ARE(I) * \mathcal{F} * \quad (TUG(I)) + 460.) ** 4 - (TW + 460.) ** 4) \text{ , Btu's/hr}$$

where $\mathcal{F}$ = EUG * VF

EUG = undergarment emissivity

VF = view factor, body to cabin

This expression is derived from analysis of one gray body completely enclosing another with the enclosing surface area (wall) much larger than the enclosed surface area (man).

2.2 SUITED MODE

The space suit is treated in much the same manner as is the man. That is, it is divided into compartments, one suit compartment for each skin compartment. This is illustrated in Figure 5.

There are several modes of space suit operation that are considered. These are as follows:

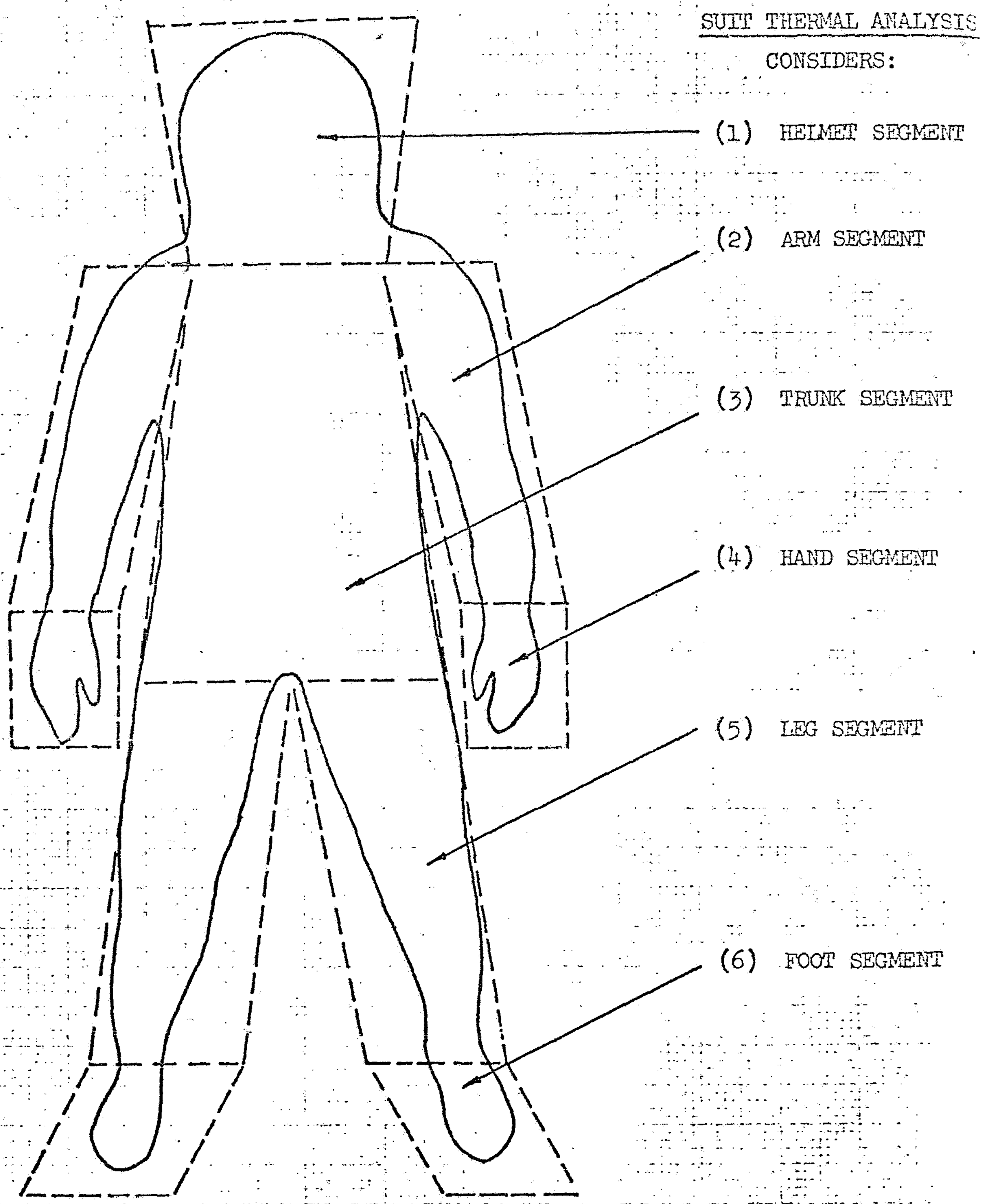
1. EVA
2. IVA
3. Helmet off
4. Purge flow

The EVA mode is utilized during extravehicular activity. Suit inlet gas from the applicable environmental control system (currently, the PLSS) enters the suit and is diverted to the helmet through a duct. The flow then passes to the trunk area and is then split, with 75% going to the arms and hands and 25% to the legs and feet, where it is collected in ducts and passed out of the suit. The flow paths are shown in Figure 6.

The IVA or intravehicular mode follows the same path as the EVA mode, except the flow is initially split between the helmet and trunk as it enters the suit. The arms and hands receive 60% of the flow, while the legs and feet receive 40%. The flow path is shown schematically in Figure 7.

The helmet off mode is shown in Figure 8. Flow is reversed so that it is directed into the ducts, over the extremities, and out of the helmet neck ring.

Purge flow operation is utilized when dry ventilation gas enters the suit and is not to be recirculated. The purge option can be used with any of the three suited modes.



SUIT THERMAL ANALYSIS
CONSIDERS:
(1) HELMET SEGMENT
(2) ARM SEGMENT
(3) TRUNK SEGMENT
(4) HAND SEGMENT
(5) LEG SEGMENT
(6) FOOT SEGMENT

FIGURE 5

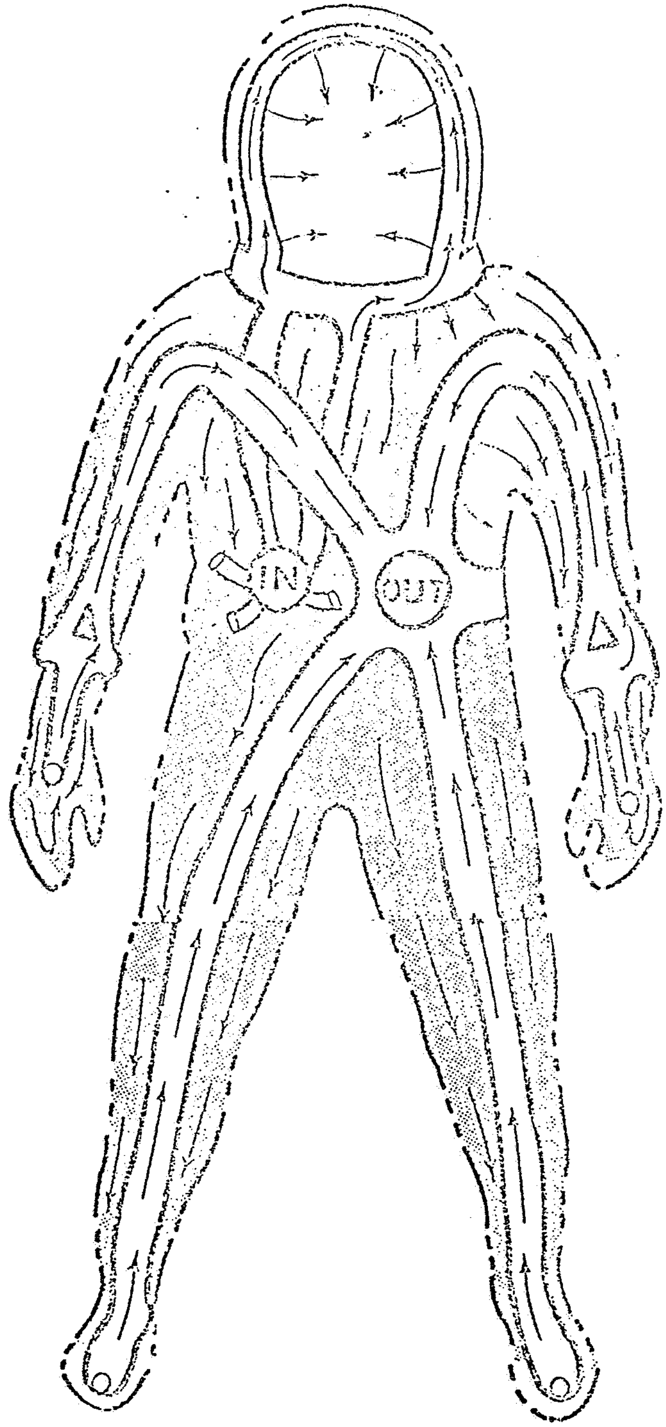
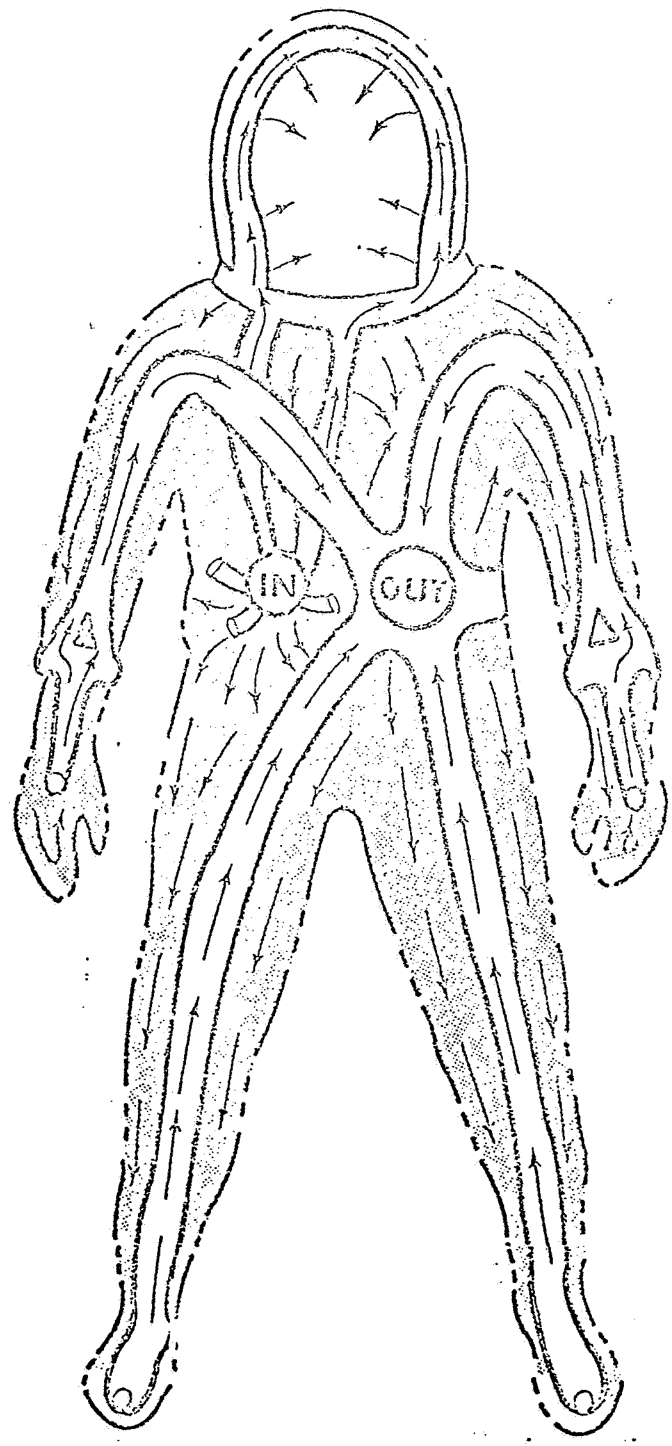


Figure 6 - Extravehicular Operation

Figure 7 - Intravehicular operation



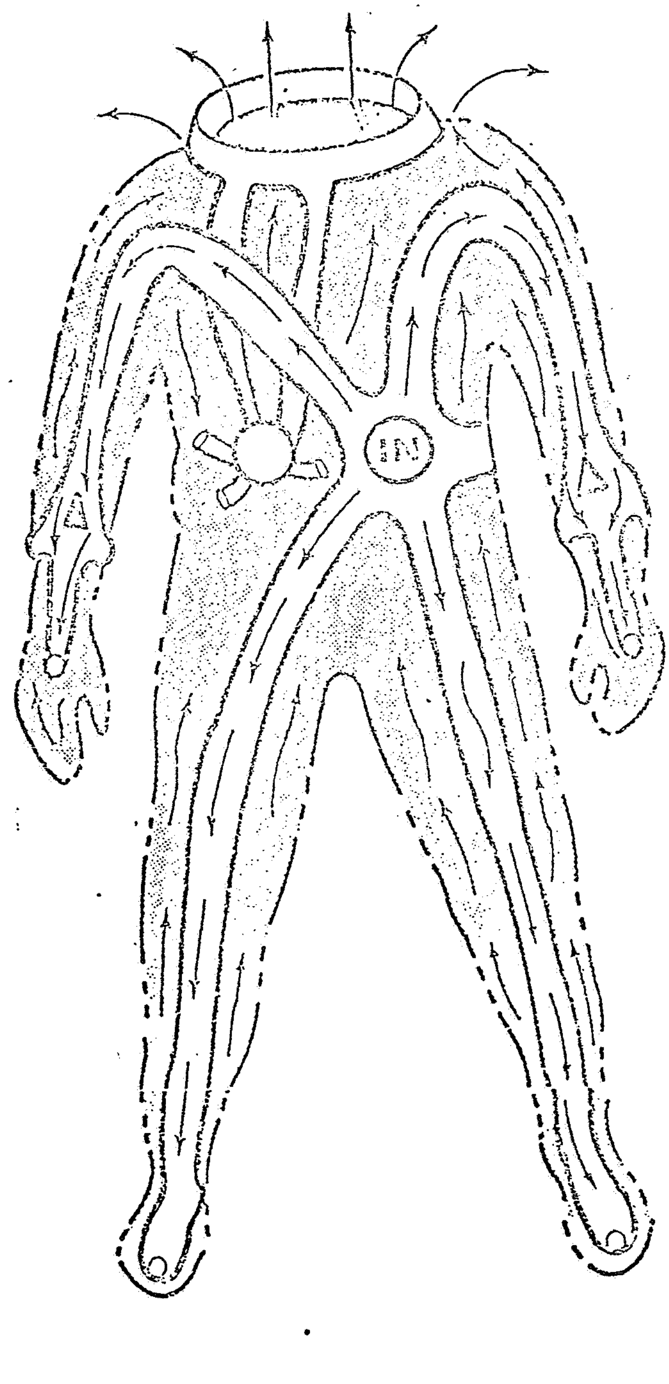


Figure 8 - Helmet-off IVA operation

The heat transfer paths for a suited crewman are considerably more complex than those for a shirtsleeve crewman. They are shown schematically in Figure 9. The suit inlet conditions are constant, or may be read in from a table. For the suited mode, the thermal environment is calculated, based on suit inlet conditions and the particular crew tasks being considered. That is, the inlet conditions for each suit compartment depend upon the outlet conditions from the previous compartment in the appropriate flow path (Figure 6, 7, or 8).

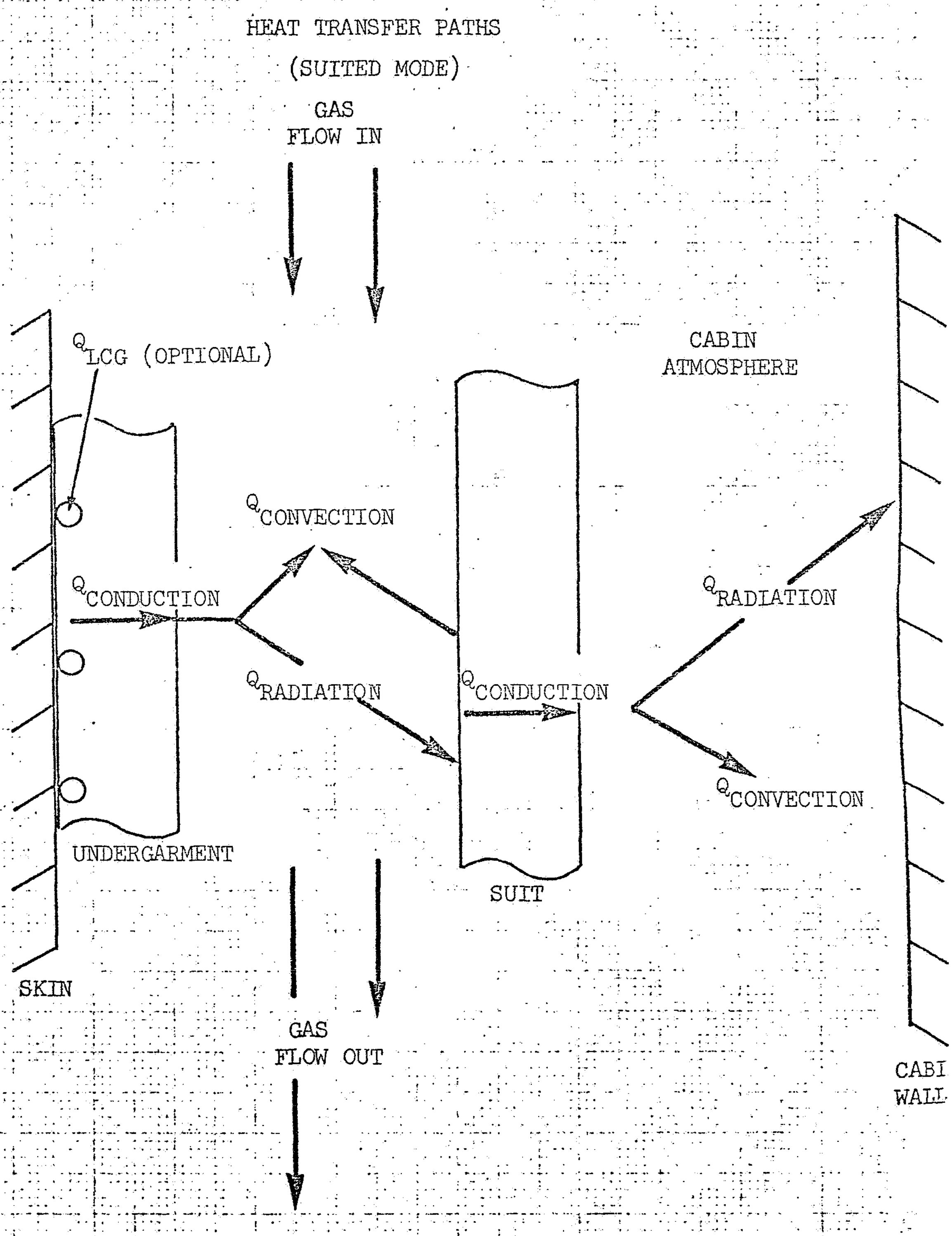

HEAT TRANSFER PATHS
(SUITED MODE)
GAS
FLOW IN
Q_{LCG} (OPTIONAL)
CABIN
ATMOSPHERE
$Q_{CONVECTION}$
$Q_{CONDUCTION}$
$Q_{RADIATION}$
$Q_{RADIATION}$
$Q_{CONDUCTION}$
$Q_{CONVECTION}$
UNDERGARMENT
SUIT
SKIN
GAS
FLOW OUT
CABI
WALL

FIGURE 9

QSEN

Convective heat transfer for each skin compartment in the suited environment is calculated from:

$$QSEN = FC(I)*(TUG(I) - TG(I)), \text{ Btu's/hr}$$

where $FC = .134 * WG**1/3 * AC(I)$

WG is the gas flow rate, in lbs/hr and

TG(I) is the log mean gas temperature for each compartment.

The heat transfer coefficient (FC) is determined by considering flow through a duct. This yields results that correspond well with test data. The log mean gas temperature, TG(I), is a complex logarithmic expression that is calculated by considering heat transfer from two flat surfaces (suit interior and skin) to an elemental volume of flowing gas. Specifically,

$$TG(I) = TM(I) - (TM(I) - TGIN(I))*WG(I) * CPG/(2. * FC(I)) * (1. - EXP(-2. * FC(I)/(WG(I) * CPG))), \ ^{o}F$$

where $TM(I) = (TUG(I) + TIS(I))/2.$

Thus, the outlet gas temperature for each suit compartment is a function of QSEN and also QISG, the convective heat transfer from the inside suit surface to the gas stream.

Accordingly, we can write for each suit compartment:

$$WG(I) * CPG * (TGOUT(I) - TGIN(I)) = QSEN + QISG$$

where $QISG = .134 * WG**1/3 * ACSUT(I) * (TIS(I) - TG(I))$.

This expression is solved for the gas stream outlet temperature, TGOUT(I), and this, in turn, is set equal to the gas stream inlet temperature for the next suit compartment in the appropriate gas flow path.

EMAX

The maximum evaporative heat capacity for the suited mode, EMAX, is calculated for each skin compartment by:

$$EMAX = WG(I) * \frac{RMIX}{18} * PG * (PH2OO(I) - PH2OI(I)) * 1040.$$

Btu's/hr

where RMIX is the gas constant and

PH2OI(I) is the water vapor partial pressure inlet to each suit compartment (in psia).

The maximum water vapor partial pressure outlet for each suit compartment, PH2OO(I), is equal to the inlet partial pressure plus the maximum quantity of water evaporated into the gas stream by mass transfer, latent respiration and diffusion. The pertinent equation for convective mass transfer is a complex logarithmic expression that considers mass transfer from an elemental area of one surface (skin) to a flowing gas.

Specifically, for each compartment;

$$PH2OO(I) = PH2OI(I) + (VPP(TUG(I)) - PH2OI(I)) *$$
$$(1. - EXP(-CMT * PG * ACE(I) * 144./(RMIX * WG(I) * (TG(I) + 460.)))),$$

CMT is the mass transfer coefficient determined to be:

$$CMT = (.00866 * WG ** 1/3 * (TG(1) + 460.) ** 1.53)/PG$$

The mass transfer coefficient is calculated by applying the heat - mass transfer analogy to the heat transfer expression for flow through a duct. Again, this gives reasonable agreement with test data. The mass transfer is considered to result from the differential between the water vapor pressure evaluated at skin temperature and a log mean gas stream partial pressure, derived in much the same manner as the log mean gas temperature described previously. As in the heat transfer analysis, the gas flow path of the appropriate suited mode is utilized. The outlet partial pressure of one suit compartment is equated to the inlet partial pressure of the next suit compartment in the flow path. However, to determine the actual partial pressure in each suit compartment (versus the maximum), the calculated value of EMAX is compared with SWEAT. The minimum of these two quantities is added to lung respiration, skin diffusion, and the inlet partial pressure to determine the correct outlet partial pressure.

It should be noted that both skin diffusion and lung respiration utilize the partial pressure calculations described above.

QRAD.

Radiation heat transfer for each skin compartment is calculated in subroutine SUIT by:

$$\mathrm{QRAD} = .1713\mathrm{E}{-8} * \mathrm{ARE(I)} * \mathcal{F} * ((\mathrm{TUG(I)} + 460.) ** 4 - (\mathrm{TIS(I)} + 460.)**4)$$

Where $\mathcal{F}$ is the interchange factor for one gray body completely surrounding another gray body of similar surface area. For the case of a space suit surrounding a man,

$$\mathcal{F} \doteq (\mathrm{EUG} * \mathrm{EIS}) \,/\, (\mathrm{EIS} + \mathrm{EUG} - \mathrm{EUG} * \mathrm{EIS})$$

The radiation heat leak of the crewman to the inside suit surface is, of course, limited by the amount of radiation that can actually get through the suit and into the environment. That is to say, the net radiation heat transfer from the man to the suit interior depends upon the suit interior surface temperature. This, in turn, depends upon the net heat leak through the suit. Consequently, we need to consider all factors affecting suit interior surface temperature. In addition to QRAD, this also includes radiation and convection from the outer suit surface to the environment (QOSW and QOSA), and convection from the inner suit surface to the suit gas stream (QISG).

The appropriate equations for each compartment are:

$$\mathrm{QOSW} = .1713\ \mathrm{E}{-8} * \mathrm{ARSUT(I)} * \mathcal{F} * ((\mathrm{TOS(I)} * 460.) ** 4 - (\mathrm{TW} + 460.) ** 4) \quad , \quad \mathrm{Btu's/hr}$$

where $\mathcal{F}$ = VF * EOS

for a suited crewman situated in an enclosed cabin; or

QOSW = .1713 E-8 * EOS * ARSUT(I) * (TOS(I) + 460.) ** 4)

- QASRB(I) * ARSUT(I), Btu's/hr

for a lunar surface or EVA case where absorbed heat, QASRB(I), is known.

QOSA = .0212 * (PCAB * VCAB) ** .5 * ACSUT(I) * (TOS(I) - TCAB), Btu's/hr

and finally,

QISG as given previously in 2.2.2.

A heat balance is performed on the outer and inner suit surfaces utilizing the above terms. The resulting equations permit computation of TIS(I) and QRAD. Specifically,

$$\frac{\text{WS * CPS}}{(\text{2.*DTIME})} \text{ * (TOS(I)}' - \text{TOS(I))}$$

$$= \text{K * } \frac{\text{ACSUT(I)}}{\text{L}} \text{ (TIS(I) - TOS(I)) - (QOSW + QOSA)}$$

and

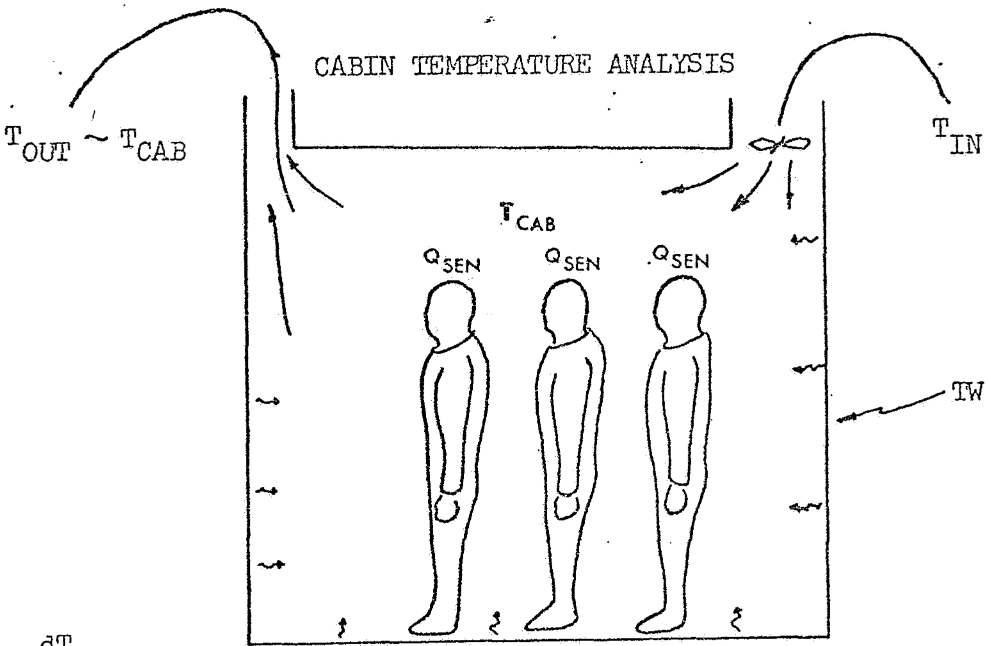
$$\frac{\text{WS * CPS}}{\text{2. * DTIME}} \text{ (TIS(I)' - TIS(I)) = QRAD - QISG - K * } \frac{\text{ACSUT(I)}}{\text{L}} \text{ *}$$

$$\text{(TIS(I) - TOS(I))}$$

where K, WS, CPS, and L are space suit properties and TOS(I)' and TIS(I)' are outer and inner suit surface temperatures computed after each time increment DTIME.

3.0 MISCELLANEOUS CALCULATIONS

In addition to the operational modes described in Sections 2.1 and 2.2, the model has the capability of computing carbon dioxide (CO_2) concentration in the space suit helmet, and carbon dioxide, humidity, and temperature levels in a post-landing or sealed environment. Carbon dioxide, water, and heat are generated by the crew into a closed environment. This closed environment may be a space suit or a spacecraft of variable volume. Depending upon the flow through the closed environment (if any), all three waste products will build up to some steady state level. The humidity and temperature determinations in a space suit have already been described. The post-landing and helmet CO_2 analyses are presented, along with their pertinent differential equations, in Figures 10, 11, and 12. As in all previous transient calculations, the program utilizes a forward difference procedure with time increment DTIME.



$$m\ C_p\ \frac{dT_{CAB}}{D_{TIME}} = NUMEN \cdot (QSEN) + \dot{m}C_pT_{IN} - Q_{WALL} + Q_{CONDNS} - \dot{m}C_pT_{CAB}$$

m = mass of aabin gas

= Volume $(P_{CAB}/(R_{MIX}\ (T_{CAB} + 460.))$, lbs

C_p = Specific heat of gas, Btu/lb - ^{o}F

T_{IN} = Gas inlet temperature

$\dot{m}$ = Gas flow through cabin, lbs/hr

NUMEN = Number of men in cabin

TW = Wall Temperature

Q_{WALL} = Heat transfer from cabin gas to wall - $h\ A_s(T_{CAB} - TW)$, Btu/hr

A_s = Cabin interior surface area

h - Flat plate heat transfer coefficient = $(.0212)\ (P_{CAB}\ V_{CAB})^{\frac{1}{2}}$ = forced convection; = $(.06)\ (P_{CAB}^{\ 2}\ (G)\ ABS^{+}(T_{CAB} - TW))^{\frac{1}{4}}$ = free convection

Q_{CONDNS} = Heat added to (removed from) gas stream as a result of water condensing (reevaporating) on the wall =

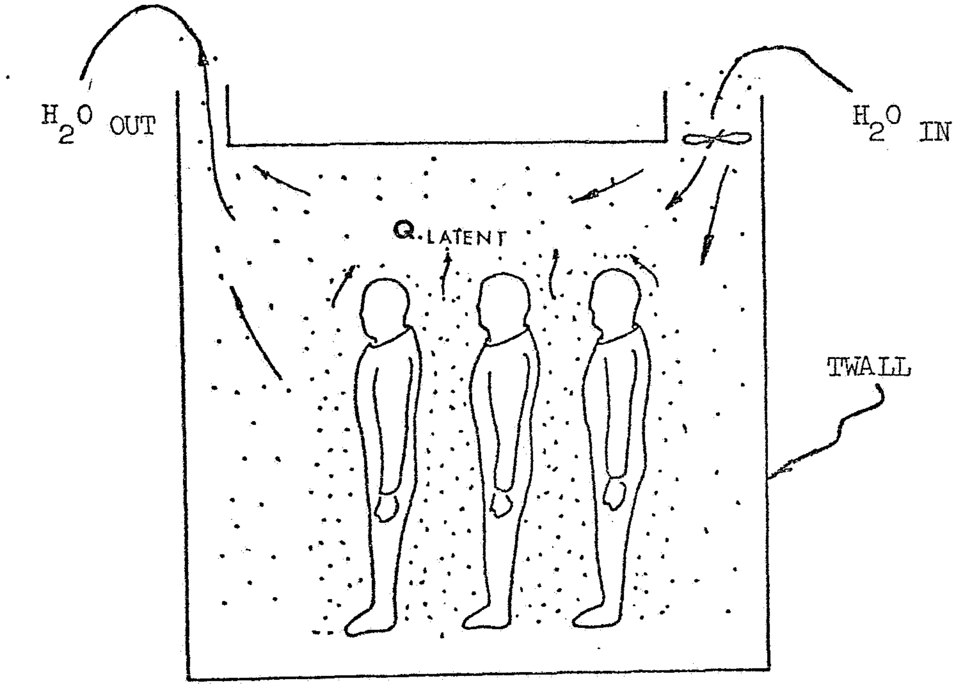
$h_DA_s(PH2O_{TDEW} - PH2O_{TW})$, Btu/hr

h_D = Flat plate mass transfer coefficient = $(.15)\ (T_{CAB} + 460.)^{1.04}$ $(V_{CAB}/P_{CAB})^{\frac{1}{2}}$ -forced convection; $= \left(\frac{1.32}{P_{CAB}}\right)\ (T_{CAB} + 460.)$ $(P_{CAB}\ \ G\ \ ABS^{+}(.005\ (PCAB)\ (PCAB - TW) + (1.02)\ (PH2O_{TDEW} -$ $PH2O_{TW}\ )))^{\frac{1}{4}}$ - free convection

FIGURE 10

+ABS denotes absolute value

CABIN DEWPOINT ANALYSIS



$$\frac{dH_2O}{D_{TIME}} = H_2O_{IN} + \text{NUMEN}\ \frac{Q_{LATENT}}{1040.} - \frac{QCONDNS}{1040.} - H_2O_{OUT}$$

H_2O = lbs of water in cabin

H_2O_{IN} = Lbs of water/hr into cabin

$\frac{QCONDNS}{1040.}$ = Lbs/hr of water condensed (reevaporated) onto walls

H_2O_{OUT} = Lbs/hr of water out of cabin

$$= \frac{H_2O}{\text{Cabin Volume}}\ \text{CFM}$$

CFM = Volumetric flow through cabin, ft^3/min

$$\text{Specific humidity in cabin} = \frac{(H_2O)\ .\ 1/144}{\text{Cabin Volume}\ \cdot\ P_{CAB}/(R_{MIX}\ \cdot\ (T_{CAB} + 460.))},$$

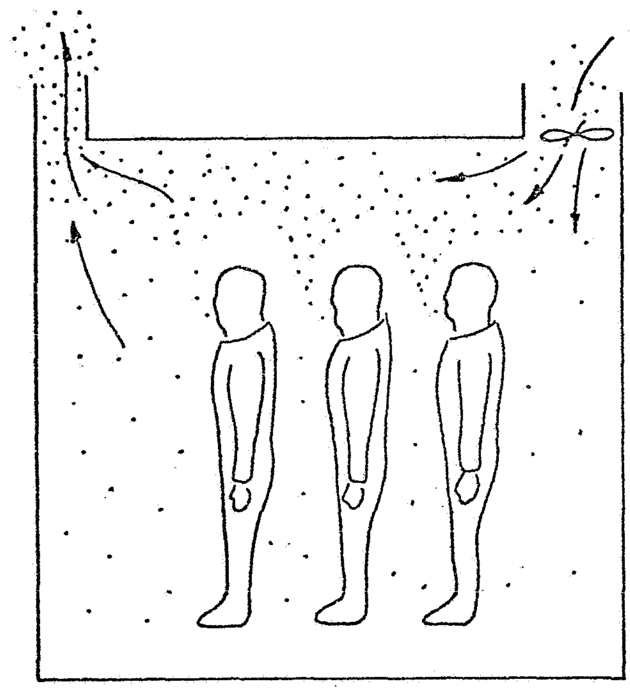
$$\frac{\text{lbs } H_2O}{\text{lbs gas}}$$

Cabin dewpoint is then determined from phychrometric charts.

FIGURE 11

CABIN/SPACE SUIT HELMET CO_2 ANALYSIS

CO_2 OUT



CO_2 IN

$$\frac{d(CO_2)}{D_{TIME}} \doteq CO_{2\ IN} + \text{NUMEN (METABOLIC } CO_2) - CO_{2\ OUT}$$

$CO_{2\ IN}$ = Atmosphere CO_2 (or helmet inlet CO_2 level), lbs/hr

Metabolic CO_2 = (.000189) RM, lbs/hr

$$CO_{2\ OUT} = \frac{CO_2}{\text{VOLUME}_{\text{cabin or helmet}}} \text{ (CFM)}, \quad \text{lbs/hr}$$

FIGURE 12

APPENDIX A

Explanation of Subscripts

For variables concerning the body (T, BF, QMET, QCOND, QLAT, QCONV, QDIF, C)

1 = head core

2 = head skin

3 = Trunk core

4 = Trunk muscle

5 = Trunk skin

6 = Arm muscle

7 = Arm skin

8 = Hand muscle

9 = Hand skin

10 = Leg muscle

11 = Leg skin

12 = Foot muscle

13 = Foot skin

14 = Central blood

15 = Average skin

16 = Average muscle

For variables concerning the garment and suit (TUG, TIS, TOS, TG, QLCG, FC, FR)

1 = Trunk zone	4 = Head zone
2 = Arm zone	5 = Hand zone
3 = Leg zone	6 = Foot zone

<u>Temperature of the Head Core</u>

$$T(1) = T(1) + \frac{DTIME}{C(1)} * (QMET(1) + QCON(1) - QLAT(1) - QCOND(1) - QRSEN1)$$

$$C(1) = 8.553$$

$$QMET(1) = 49.2825$$

$$QLAT(1) = 0.5 * 0.0418 * PCAB * 144.0/(48.3 * (ICAB + 460.0)) * RM * VPP\ (T(1) + T(3))/2.0) - 0.8 * VPP\ (TDEWC) * ((18.0 * 1040.0)/(3210 * PCAB))$$

For shirtsleeves and helmet off

$$\text{or } QLAT(1) = 0.5 * 0.0418 * PG * 144.0/(48.3 * (TG(4) + 460.0)) * RM * (VPP\ ((T(1) + T\ (3))/2.0) - 0.8 * ((PH2OI(4) + AMINI\ (PH2O4,\ PH2OO(4)))/2.0)) * ((18.0 * 1040.0)/(32.0 * PG))$$

For normal suited IVA and EVA modes

$$QCONV(1) = BF(1) * (T(14) - T(1))$$

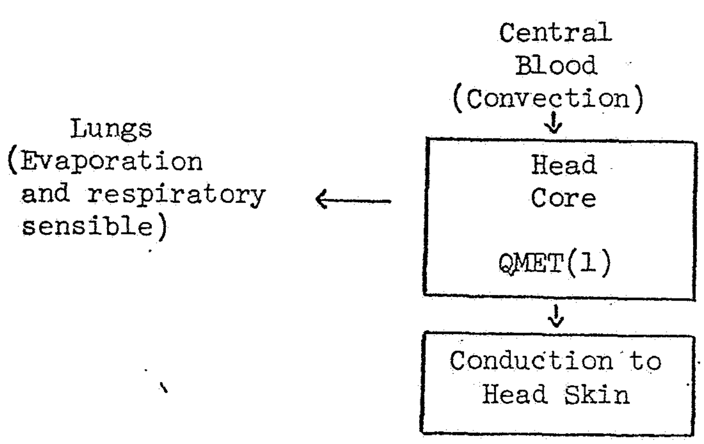
$$QCOND(1) = 5.798 * (T(1) - T(2))$$

QRSEN1 = For normal suited IVA and EVA modes

$$0.5 * 0.0418 + PG * 144.0/(48.3 * (TG(4) + 460.0)) * RM * (((T(1) + T(3))/2.0) - TG(4)) * CPG$$

= For shirtsleeves and helmet off

$$0.5 * 0.0418 * PCAB * 144.0/(48.3 * (TCAB + 460.0)) * RM * (((T(1) + T(3))/2.0) - TCAB) * CPG$$



Temperature of the Head Skin

$$T(2) = T(2) + \frac{DTIME}{C(2)} * (QCOND(1) + QMET(2) + QCONV(2) - QLAT(2) - QSEN(2) - QRAD(2) - QLCG(4))$$

C(2) = 0.5511

QCOND(1) = 5.798 * (T(1) - T(2))

QMET(2) = 0.3968

QLAT(2) = QDIF(2) + AMIN1 (0.1 * SWEAT, EMAX(2))

QCONV(2) = BF(2) * (T(14) - T(2))

QSEN(2) = HC * (TUG(4) - TCAB) For shirtsleeves and helmet off

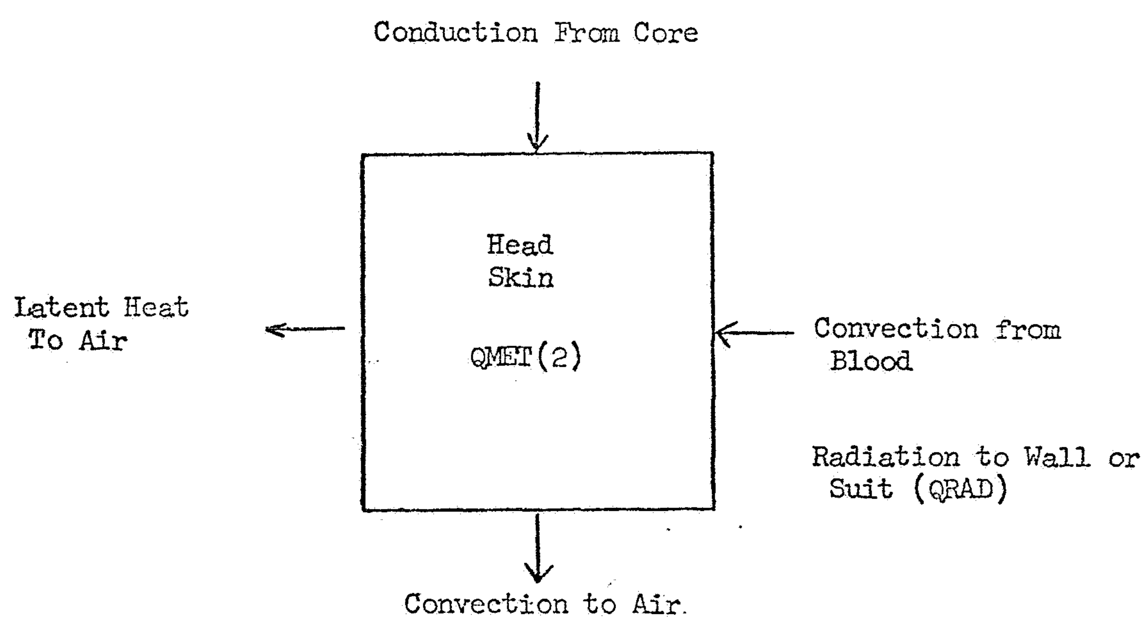
= FC(4)*(TUG(4) - TG(4)) For suited EVA and IVA

QRAD(2) = HR * (TUG(4) - TW) For shirtsleeves and helmet off

FR(4) * ((TUG(4) + 460.0) ** 4 - (TIS(2) + 460.0) ** 4)

For suited IVA and EVA

QLCG(4) = 0.0



Temperature of the Trunk Core

$$T(3) = T(3) + \frac{DTIME}{C(3)} * (QMET(3) - QCONV(3) + QLAT(3) - QCOND(3) - QRSEN3$$

$$C(3) = 45.3004$$

$$QMET(3) = 179.3536$$

$$QLAT(3) = 0.5 * 0.0418 * PCAB * 144.0/(48.3 * (ICAB + 460.0)) * RM *$$

$$VPP\ (T(1) + T(3))/2.0 - 0.8 * VPP\ (TDEWC) * ((18.0 * 1040.0)/$$

$$(3210 * PCAB))$$

For shirtsleeves and helmet off

$$\text{or } QLAT(3) = 0.5 * 0.418 * PG * 144.0/(48.3 * (TG(4) + 460.0)) * RM *$$

$$VPP\ ((T(1) + T(3))/2.0) - 0.8 * ((PH2OI(4) + AMINI$$

$$(PH2O4, PH2OO(4)))/2.0)) * ((18.0 * 1040.0)/(32.0 * PG))$$

For normal suited IVA and EVA modes

$$QCONV(3) = BF(3) * (T(14) - T(3))$$

$$QCOND(3) = 10.691 * (T(3) - T(4))$$

QRSEN3 = For normal suited IVA and EVA modes

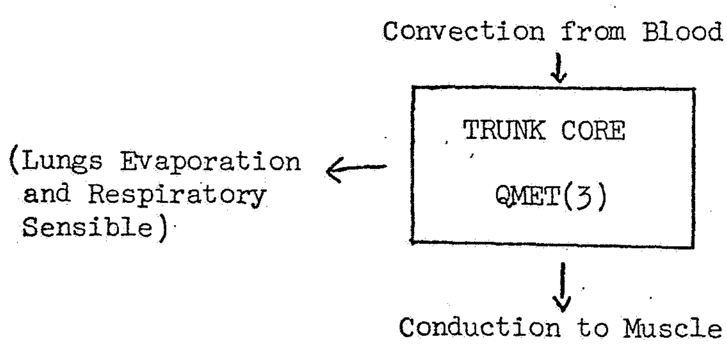
$$0.5 * 0.0418 + PG * 144.0/(48.3 * (TG(4) + 460.0)) * RM *$$

$$(((T(1) + T(3))/2.0) - TG(4)) * CPG$$

= For shirtsleeves and helmet off

$$0.5 * 0.0418 * PCAB * 144.0/(48.3 * (TCAB + 460.0)) * RM *$$

$$(((T(1) + T(3))/2.0) - TCAB) * CPG$$



<u>Temperature of the Trunk Muscle</u>

$$T(4) = T(4) + \frac{DTIME}{C(4)} * (\ QCOND(3) + QMET(4) + QCONV(4) - QCOND(4))$$

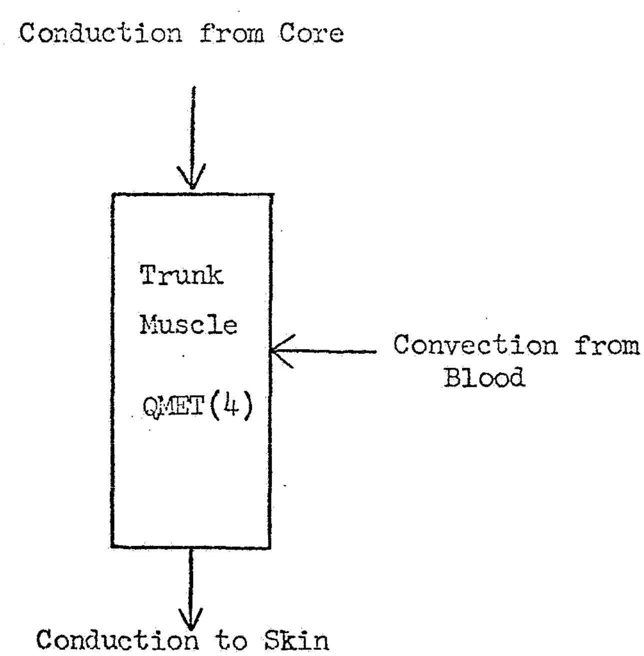
C(4) = 21.9337

QCOND(3) = 10.691 * (T(3) - T(4))

QMET(4) = 17.0624 + 0.417 * (WORK + QSHIV)

QCONV(4) = BF(4) * (T(14) - T(4))

QCOND(4) = 29.759 * (T(4) - T(5))



Temperature of the Trunk Skin

T(5) = T(5) + $\frac{\text{DTIME}}{\text{C(5)}}$* (QCOND(4) + QMET(5) + QCONV(5) - QLAT(5) - QSEN(5) - QRAD(5) - QLCG(1))

C(5) = 2.8216

QCOND(4) = 29.759 * (T(4) - T(5))

QMET(5) = 2.0236

QLAT(5) = QDIF(5) + AMIN1 (0.6 * SWEAT, EMAX(5))

QCONV(5) = BF(5) * (T(14) - T(5))

QSEN(5) = HC * TUG(1) - TCAB For shirtsleeves

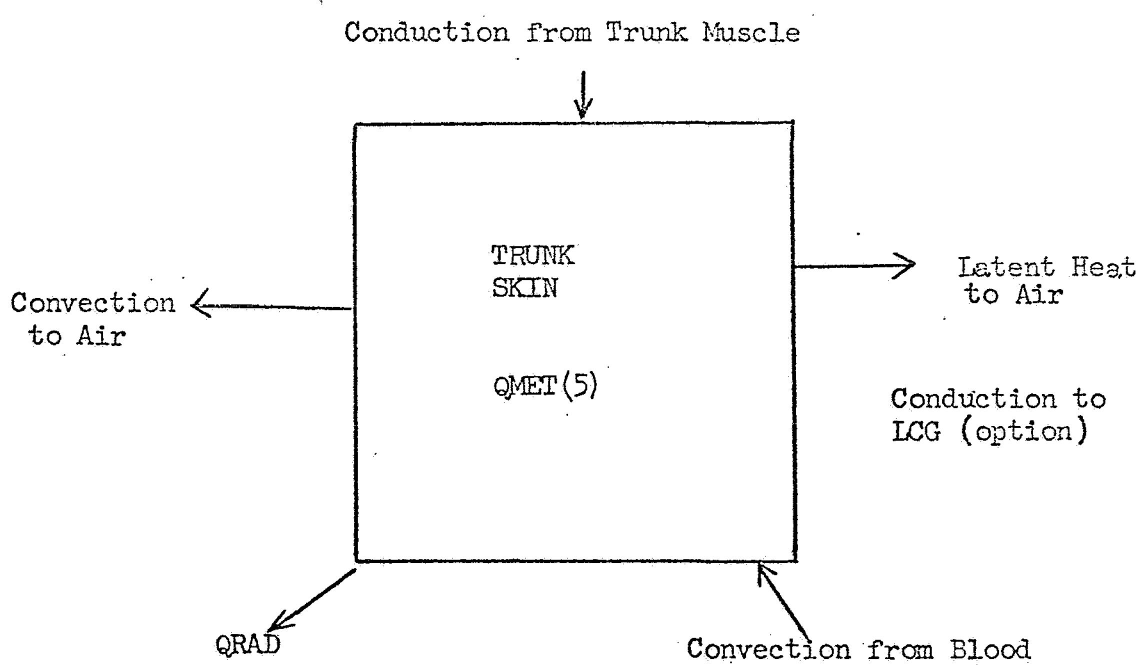
FC(1)*(TUG(1) - TG(1)) For suited

QRAD(5) = HR * (TUG(1) - TW) For shirtsleeves

FR(1) * ((TUG(1) + 460.0) ** 4 - (TIS(1) + 460.0) ** 4)

For suited modes

QLCG(1) = PCFLO(1) * WF * CPW *(TWO - TWI)



Temperature of the Arm Muscle

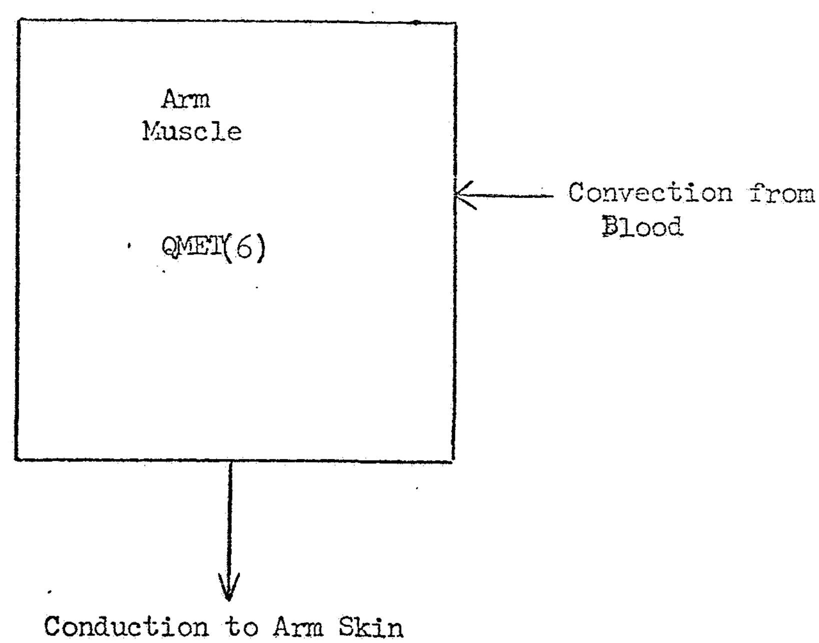
$$T(6) = T(6) + \frac{DTIME}{C(6)} * (QMET(6) + QCONV(6) - QCOND(6))$$

$$C(6) = 8.553$$

$$QMET(6) = 6.19 + 0.19 * (WORK + QSHIV)$$

$$QCONV(6) = BF(6) * (T(14) - T(6))$$

$$QCOND(6) = 9.699 * (T(6) - T(7))$$



Temperature of the Arm Skin

$$T(7) \quad T(7) + \frac{DTIME}{C(7)} * (QCOND(6) + QMET(7) + QCONV(7) - QLAT(7) - QSEN(7) - QRAD(7) - QLCG(2))$$

$$C(7) = 1.7194$$

$$QCOND(6) = 9.699 * (T(6) - T(7))$$

$$QMET(7) = 1.23$$

$$QLAT(7) = QDIFF(7) + AMIN1\ (0.1 * SWEAT,\ EMAX(7))$$

$$QCONV(7) = BF(7) * (T(14) - T(7))$$

$$QSEN(7) = HC * (TUG(2) - TCAB) \qquad \text{For shirtsleeves}$$

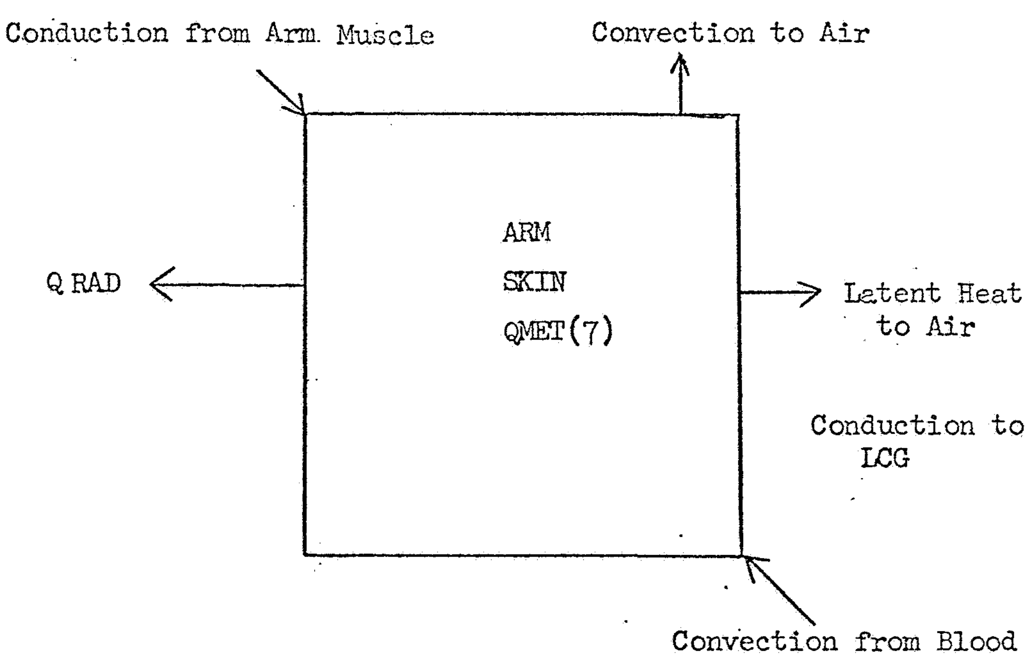
$$= FC(2) * (TUG(2) - TG(2)) \qquad \text{For suited modes}$$

$$QRAD(7) = HR * (TUG(2) - TW) \qquad \text{For shirtsleeves}$$

$$= FR(2) * ((TUG(2) + 460.0) ** 4 - (TIS(2) + 460.0) ** 4)$$

For suited modes

$$QLCG(2) = PCFLO(2) * WF * CPW * (TWO - TWI)$$



Temperature of the Hand Muscle

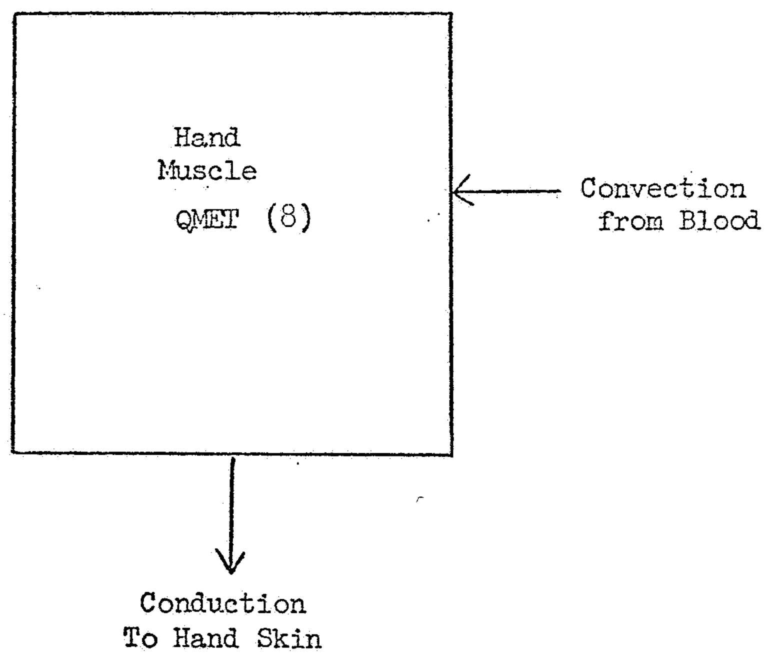
$$T(8) = T(8) + \frac{DTIME}{C(8)} * (QMET(8) + QCONV(8) - QCOND(8))$$

C(8) = 3.2184

QMET(8) = 2.3014

QCONV(8) = BF(8) * (T(14) - T(8))

QCOND(8) = 6.349 * (T(8) - T(9))



Temperature of the Hand Skin

$$T(9) = T(9) + \frac{DTIME}{C(9)} \quad (QCOND(8) + QMET(9) + QCONV(9) - QLAT(9) - QSEN(9) - QRAD(9) - QLCG(5))$$

C(9) = 0.4408

QCOND(8) = 6.349 * (T(8) - T(9))

QMET(9) = 0.3174

QLAT(9) = QDIF(9) + AMIN1 (0.02 * SWEAT, EMAX(9))

QCONV(9) = BF(9) * (T(14) - T(9))

QSEN(9) = HC * (TUG(5) - TCAB) For shirtsleeves

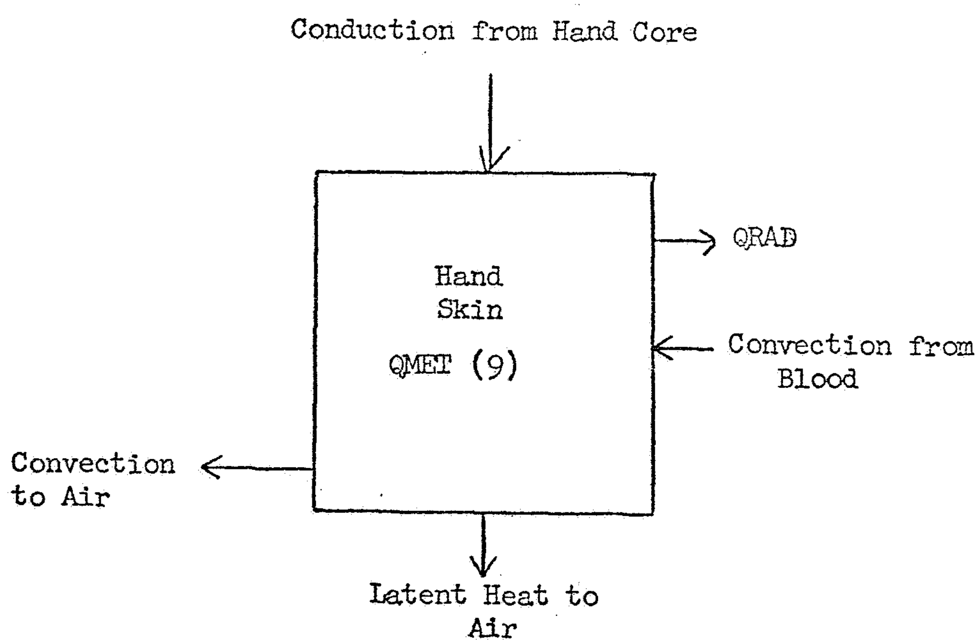
= FC(5) * (TUG(5) - TG(5)) For suited mode

QRAD(9) = HR * (TUG(5) - TW) For shirtsleeve

= HR(5) * ((TUG(5) + 460.0) ** 4 - (TIS(5) + 460.0) ** 4)

For suited modes

QLCG(5) = 0.0



Temperature of the Leg Muscle

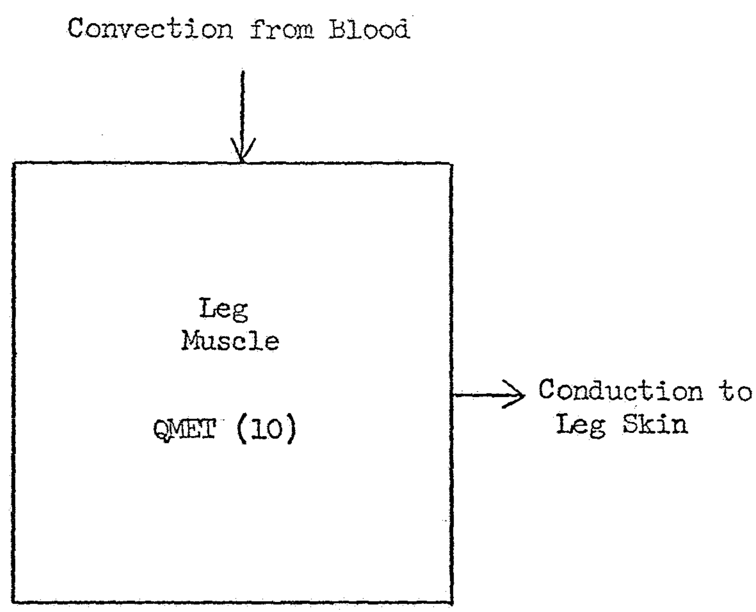
$$T(10) = T(10) + \frac{DTIME}{C(10)} * (QMET(10) + QCONV(10) - QCOND(10))$$

$$C(10) = 25.4608$$

$$QMET(10) = 18.5702 + 0.393 * (WORK + QSHIV)$$

$$QCONV(10) = BF(10) * (T(14) - T(10))$$

$$QCOND(10) = 9.435 * (T(10) - T(11))$$



Temperature of the Leg Skin

$$T(11) = T(11) + \frac{DTIME}{C(11)} \left(QCOND(10) + QMET(11) + QCONV(11) - QLAT(11) - QSEN(11) - QRAD(11) - QLCG(3) \right)$$

$C(11) = 3.9017$

$QCOND(10) = 9.435 * (T(10) - T(11))$

$QMET(11) = 2.8172$

$QLAT(11) = QDIF(11) + AMIN1\ (0.16 * SWEAT,\ EMAX(11))$

$QCONV(11) = BF(11) * (T(14) - T(11))$

$QSEN(11) = HC * (TUG(3) - TCAB)$ For shirtsleeves

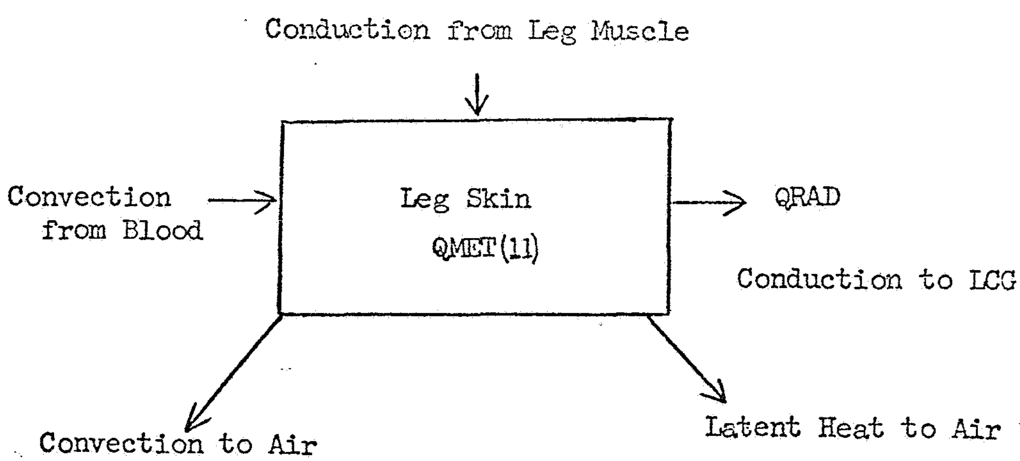
$FC(3) * (TUG(3) - TG(3))$ For suited modes

$QRAD(11) = HR * (TUG(3) - TW)$ For shirtsleeves

$FR(3) * ((TUG(3) + 460.0) ** 4 - (TIS(3)+460.0) ** 4)$

For suited modes

$QLCG(3) = PCFLO(3) * WF * CPW * (TWO - TWI)$



Temperature of the Foot Muscle

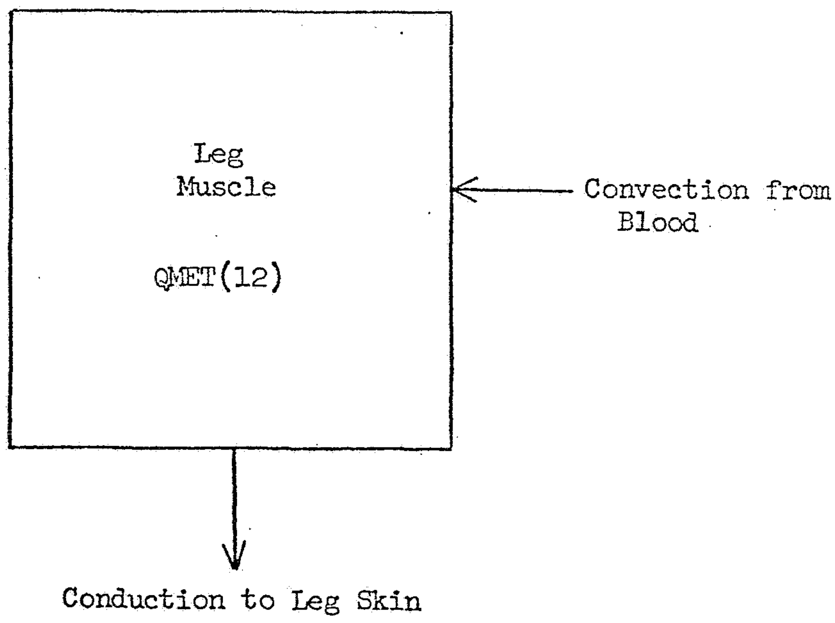
$$T(12) = T(12) + \frac{DTIME}{C(12)} * (QMET(12) + QCONV(12) - QCOND(12))$$

$$C(12) = 6.2825$$

$$QMET(12) = 4.5235$$

$$QCONV(12) = BF(12) * (T(14) - T(12))$$

$$QCOND(12) = 4.766 * (T(12) - T(13))$$



Temperature of the Foot Skin

$$T(13) = T(13) + \frac{DTIME}{C(13)} * (\,QCOND(12) + QMET(13) + QCONV(13) - QLAT(13) - QSEN(13) - QRAD(13) - QLCG(6))$$

$$Q(13) = 0.6613$$

$$QCOND(12) = 4.762 * (T(12) - T(13))$$

$$QMET(13) = 0.4761$$

$$QLAT(13) = QDIF(13) + AMIN1\ (0.02 * SWEAT,\ EMAX(13))$$

$$QCONV(13) = BF(13) * (T(14) - T(13))$$

$$QSEN(13) = HC * (TUG(6) - TCAB) \quad \text{For shirtsleeves}$$

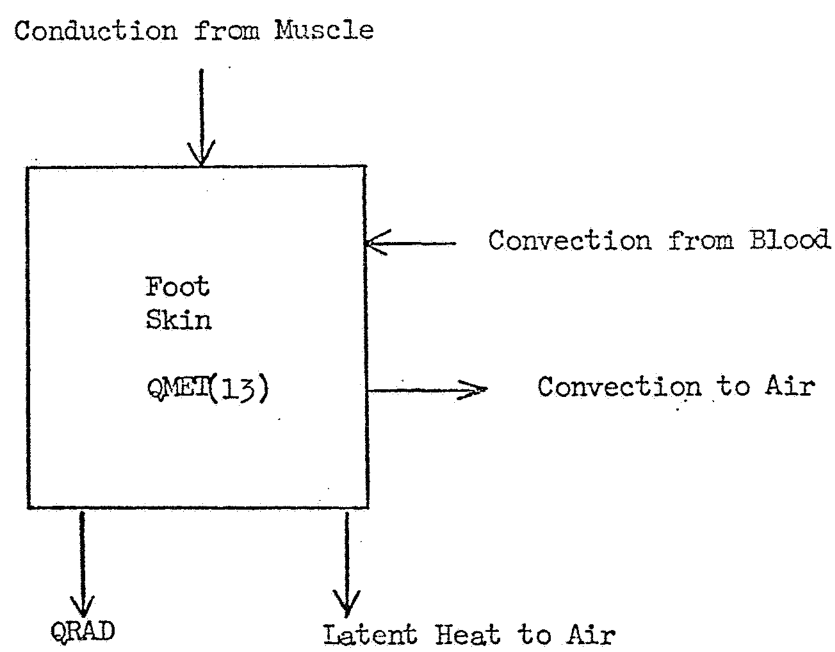
$$FC(6) * (TUG(6) - TG(6)) \quad \text{For suited modes}$$

$$QRAD(13) = HR * (TUG(6) - TW) \quad \text{For shirtsleeves}$$

$$FR(6) * (TUG(6) * 460.0) ** 4 - (TIS(6)+460.0)** 4)$$

For suited modes

$$QLCG(6) = 0.0$$



Temperature of the Central Blood

$$T(14) = T(14) + \frac{DTIME*(}{C(14)} \quad - \sum_{I=1}^{13} \quad (QCONV(I))$$

QCONV(I) = BF(I) * (T(14) - T(I))

BF(1) = 105.897

BF(2) = 2.647 + 0.056 * DILAT

BF(3) = 503.013

BF(4) = 22.062 + QMET(4)

BF(5) = 2.2062 + 0.3 * DILAT - STRIC

BF(6) = 6.618 + QMET(6) + BF(9) - STRIC

BF(7) = 1.103 + 0.2 * DILAT - STRIC

BF(8) = 1.103 - STRIC

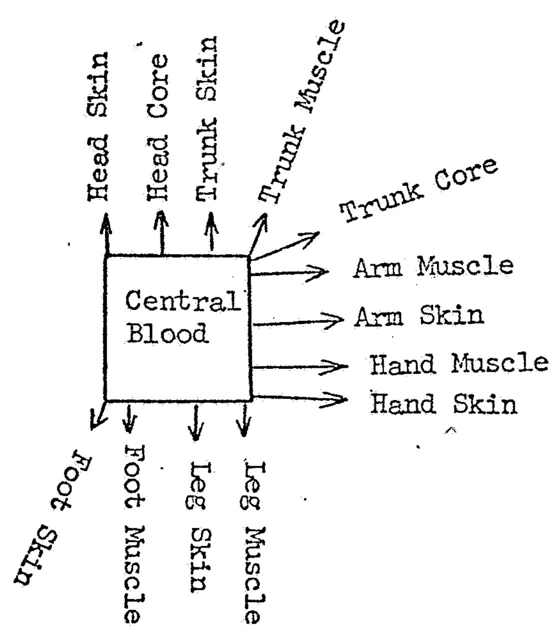
BF(9) = 8.824 + 0.1 * DILAT - STRIC

BF(10) = 17.649 + QMET(10) + BF(13) - STRIC

BF(11) = 2.206 + 0.294 * DILAT - STRIC

BF(12) = 2.206 - STRIC

BF(13) = 6.618 + 0.05 * DILAT - STRIC



Average Skin Temperature

$$T(15) = 0.056 * T(2) + 0.276 * T(5) + 0.173 * T(7) + 0.043 * (T(9) + 0.383 * T(11) + 0.069 * T(13)$$

Average Muscle Temperature

$$T(16) = 0.471 * T(4) + 0.136 * T(6) + 0.393 * T(10)$$